EXAMINING THE RELATIVE COSTS AND BENEFITS OF SHIFTING THE LOCUS OF CONTROL IN A NOVEL AIR TRAFFIC MANAGEMENT ENVIRONMENT VIA MULTI-AGENT DYNAMIC ANALYSIS AND SIMULATION

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To my wife, Rose, whom I love dearly and who will probably never read this but hopefully understands how much I appreciated her patience and understanding while I was working on this project.

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NOMENCLATURE

ANSP	Air Navigation Service Provider
AOP	Autonomous Operations Planner
BADA	Base of Aircraft DAta
CD&R	Conflict Detection and Resolution
CTAS	Center-TRACON Automation System
ETMS	Enhanced Traffic Management System
FL	Flight Level
IFR	Instrument Flight Rules
ISyE	Industrial & Systems Engineering
IT	Information Technology
KML	Keyhole Markup Language
NASA	National Aeronautics and Space Administration (USA)
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
ODBC	Open DataBase Connectivity
SMP	Symmetric MultiProcessing
SQL	Structured Query Language
TEM	Total Energy Model
TMX	Traffic Manager eXecutable
TRACON	Terminal Radar Approach CONtrol
VFR	Visual Flight Rules
WMC	Work Models that Compute
Conflict	When the intended flight paths of two aircraft will result in a loss of separation

Flight Plan — An ordered collection of waypoints that provides the skeleton for a trajectory

Leg — A section of a flight plan between two adjacent waypoints

Loss of Separation — When two aircraft are located ≤ 5nmi laterally and/or ≤ 1000ft vertically from each other

Waypoint — A four-dimensional point including latitude, longitude, altitude, and time

SUMMARY

A common framework is needed by which to judge the relative costs and benefits of a wide range of innovative air traffic concepts of operation. For example, far-term operational concepts may significantly vary the ‘locus of control’ – whether air traffic control decisions to resolve conflicts should be centralized or de-centralized and distributed. However, current analysis methods implicitly depend upon present-day constructs such as current airway and sector structures. Further, the framework should support analysis methods providing direct and fair comparison of operational concepts when applied to the same scenarios, including weather and traffic load. The objective of this thesis is to construct a formal framework to examine innovative operational concepts, using as an example a study of the relative costs and benefits of shifting the locus of control in novel air traffic management operating concepts. This framework provides key definitions and specific quantitative measures by which concepts may be compared, and is applied here to concepts ranging between completely centralized and completely decentralized. Multi-agent analysis and simulation is applied to estimate the metrics. The framework is demonstrated to have the ability to identify (or dispel) hypotheses about the relative costs and benefits of locus of control.

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The current air traffic management system has primarily evolved via incremental changes to historic control, navigation, and surveillance technologies. As a result, the system as a whole is not capable of handling air traffic capacities well beyond current levels, despite recent developments that could potentially enable new concepts of operation. For example, new technologies such as ADS-B enable pilots to become aware of surrounding air traffic, allowing traffic flow management, trajectory planning, and conflict avoidance measures to be performed in the cockpit instead of only on the ground.

Applying these enabling technologies requires a complete reexamination of the air traffic management control paradigm. However, methods of analyzing air traffic for safety and performance have also evolved around current-day operating constructs. Thus, attempts to examine future systems tend to use different analysis methods developed for each. Most notably, questions of 'locus of control' – whether the control should be centralized or de-centralized and distributed – have no common framework by which to judge relative costs and benefits. For instance, a completely centralized control paradigm is commonly asserted to provide an airspace-wide optimal traffic management solution due to a more complete picture of the state of the airspace, whereas a completely decentralized control paradigm is commonly asserted to provide a more user-specific optimal traffic management solution, to distribute the traffic management workload, and potentially be more robust. Given the disparate nature of these assertions and the different types of evaluations commonly used with each, a shared framework must be established to allow comparisons between very different control paradigms. This framework must provide the analysis method and simulation tool that enables these comparisons via rigorous, quantitative assessments.

1.2 Background

Given the cost, risk and difficulty in transitioning to new operational concepts, the ability to systematically compare the costs and benefits of each is crucial to planning, policy development and stakeholder negotiations [20]. Although frameworks have been developed for analyzing air traffic management concepts [14], they are still tied to current-day operations. For example, estimates of close approach probability are highly dependent upon assumptions about total navigation system error distribution, which can change when new operational concepts modify methods of navigation and separation assurance [2]. Similarly, airspace design processes provide systematic methods for analysis of operational concepts, but include current day constructs such as sectors and sector complexity limits [24]. Cost-benefit analyses to date have focused on near- or mid-term concepts, and commonly involve subject matter expert ratings of projected differences from the current day [23].

While near-term improvements to air traffic operational concepts will tend to be incremental, far-term concepts capable of providing the '2X' and '3X' increases in capacity may be 'innovative' in that they change fundamental constructs underlying current-day operations. For example, innovative concepts may involve dramatic shifts in roles and responsibilities between air and ground, and between humans and automation. For example, some work has been done on new air traffic concepts of operation such as sector-less air traffic management [6] and automated airspace [7].

The test case used in this thesis is an analysis of locus of control. Centralized concepts generally require the ability for a centralized decision maker (typically automated) to predict and select trajectories for all aircraft in the airspace, which are then communicated to the aircraft for each to follow [11, 7]. Their development often depends on accurate trajectory prediction and trajectory following, and hence metrics of centralized concepts often evaluate reductions in variance about the globally-optimized traffic flow.

In contrast, decentralized operational concepts build on the historic notion of 'Free Flight,' in which aircraft are free to select their own trajectories, subject to some constraints during either maneuver selection or execution to ensure separation assurance. Decentralized concepts generally distribute to each aircraft the ability to select its trajectory – notably based upon evaluations of separation assurance constraints – and provide authority for each aircraft to exercise this ability. As such, initial evaluations focused significantly on airborne conflict detection and resolution capabilities [18]. In examining their implementation in busy airspace, studies have also examined the need for coordinated or collaborative resolutions to conflicts [27], and have debated the extent to which distributed control may be stronger or weaker in busy airspace [12]. Metrics generally examine those deviations that arise in each aircraft's locally-optimal trajectory for separation assurance, and robustness to degraded modes or disturbances.

While studies have examined centralized and decentralized concepts of operation, their direct comparison is difficult. As noted above, studies of centralized and decentralized operational concepts often use different performance metrics, and have inherent differences in whether they examine, for example, structured versus unstructured traffic flows, or nominal performance versus degraded operations. Studies have examined centrally controlled airspace concepts, [4] as well as decentralized airspace concepts [3, 15] without extensively comparing between them. Further, where comparison between centralized and decentralized operational concepts has been conducted, differences in their metrics may have been due to their different algorithms for conflict detection and resolution (CD&R) and trajectory determination, rather than the locus of control itself [17].

A wide-range of analysis methods is available for evaluating many operational concepts. Of interest here are those that can be applied well before committing significant implementation and development cost. Some methods can be analytic, such as formal methods of analyzing the flexibility, potential robustness or complexity of airspace configurations [5, 19]. However, such formal analyses generally look at fairly localized or stylized aspects of the airspace behavior. Additionally, formal analyses are unable to capture any unexpected behavior that the system exhibits beyond, for example, analyzing for the system's required maneuvering in response to predicted perturbations [19].

Some analysis methods address the limits on 'complexity' that a sector (or other volume, including multiple sectors) can achieve. For example, multiple linear regression of a number of traffic factors has been shown to predict airspace complexity within established air traffic structures [16]. Such complexity measures can potentially then become the control variable regulated by centralized algorithms for traffic flow [8], or provided as an improved estimate of airspace capacity for use by (human) traffic flow managers [25].

Other analysis methods focus on safety. For example, fault tree analysis has been applied to ADS-B based surveillance applications as a systematic process for analyzing for hazards and their underlying basic causes in a manner particularly suited to analyzing technical reliability [10]. Examining for safety in a broader context, other studies have pointed to cases where safety (or the lack thereof) can be an emergent effect, i.e., that safety issues may arise even when no component has failed due to complex, unexpected interactions between components [13, 22]. In air traffic management, specific methods for addressing emergent safety concerns include formal methods of constructing 'safety cases' or 'safety arguments' [9], and systemic accident modeling through extensive Monte Carlo simulations [26]. However, these methods are focused on safety, without simultaneously providing other measures of concepts of operation that would also factor into a cost-benefit analysis.

Simulations of air traffic may provide the detail required for the direct comparison of the relative costs and benefits in disparate, innovative air traffic concepts of operation. Historically, these simulations were typically based on discrete-event formalisms which are particularly suited for estimating capacity and delay within established network or airspace structures [1], or examined trajectories in specific constructs such as scheduled traffic in comparatively centralized operational concepts [11]. However, some agent-based simulations have been applied to the evaluation of transformations in airspace operations, and allow for disparate concepts to be modeled explicitly by, for example, relocating the locus of control [22].

1.3 Fully-Centralized and Fully-Decentralized Control Examples

The centralized operational concept extreme is a control paradigm that is similar to positive control in current (IFR) air traffic control operations. All the traffic data is gathered at a central point via radar, radio, or other means and conflict detection and resolution decisions are made using all the gathered data at a centralized point. In current day operations, this central mechanism is an air traffic controller. The decisions are then transmitted back to the appropriate aircraft where each aircraft is expected to comply with the request or give sufficient reason for non-compliance.

An example of how centralized control has been analyzed to date is the development of the center-TRACON automation system (CTAS). CTAS is a toolset that uses trajectory prediction to alert controllers of potential conflicts and suggest resolutions to those conflicts. This particular toolset was analyzed using both simulated and live traffic scenarios and found to be prone to inaccurate trajectory predictions due to external aircraft disturbances [4]. Reports of this analysis made no mention of mixed-equipage, or aircraft capable of operating in either centralized or decentralized environments.

The other locus of control extreme is a decentralized approach to air traffic management. This concept is similar to VFR operations today where pilots are responsible for seeing and avoiding other aircraft in their vicinity. The decentralized control paradigm typically involves onboard equipment capable of detecting (seeing) other aircraft and possibly executing maneuvers to avoid them. The information for all proximate aircraft is gathered at each aircraft where the conflict detection and avoidance decisions are made and executed. No communication is necessary for this control paradigm to work at a most basic level, but some communication may be desired to enable some coordination between aircraft.

A decentralized control analysis example is NLR's free flight analysis [12]. Using the traffic manager executable (TMX), a multi-agent simulation, many different aspects of decentralized control were analyzed with the possibility of handling mixed equipage.

However, TMX currently does not have a central air traffic controller implementation and therefore no capability of evaluating a variety of locus of control concepts.

Although fully-centralized and fully-decentralized control are two contrasting concepts for air traffic control, other concepts can incorporate some combination of both centralized and decentralized control, creating a range of possible control methods. For example, a certain number of aircraft can be under a centralized scheme while the remaining aircraft are under a decentralized scheme. A particular aircraft in a notional airspace may not only select the desired control scheme, but also change the control scheme en route because of restrictions (certain airspace types may require a certain number or percentage of aircraft to be under a certain control scheme e.g. 75% centralized), or because a different control scheme becomes more advantageous. Another variation examines airspace operations in greater detail and classifies specific tasks or functions as either centralized or decentralized; for example, “strategic” functions may be centralized and nearer-term functions decentralized, or vice-versa. Although many different ways of varying the locus of control exist, this thesis examines the method of each aircraft being under either centralized or decentralized control, but allows for a mix of locus of control between aircraft.

1.4 Objectives

The objective of this thesis is to construct a formal framework to examine the relative costs and benefits of innovative air traffic concepts of operation. This thesis uses as a test case shifts in the locus of control in a novel air traffic management environment. This framework provides useful definitions and quantitative measures of flexibility and robustness with respect to various control paradigms ranging between, and including, completely centralized and completely decentralized concepts of operation. Multi-agent dynamic analysis and simulation is used to analyze the range of dynamics found in the different control paradigms. In addition, futuristic air traffic management concepts are developed in sufficient detail to demonstrate the framework. In other words, the objectives are achieved when the framework is demonstrated to have the ability to identify (or dispel) hypotheses about the relative costs and benefits of innovative air traffic concepts of operation.

CHAPTER 2

FRAMEWORK

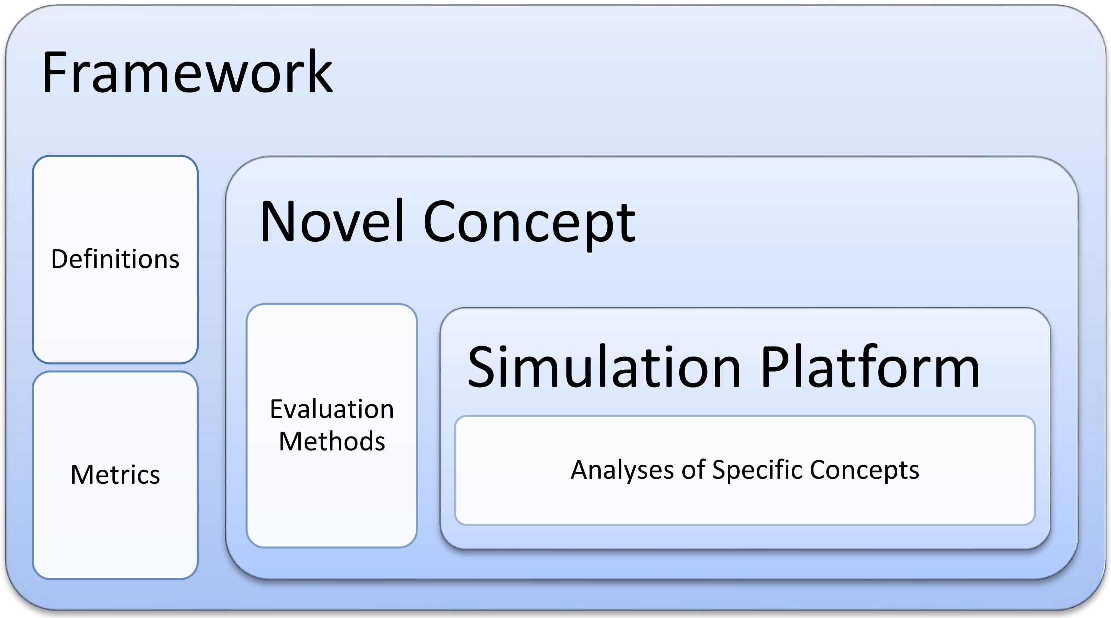


Figure 1 Framework components

The framework for this thesis is based on the components illustrated in Figure 1. At its most general level, the framework provides *definitions* of essential aspects of airspace and describes the *metrics* necessary to assess relative performances of airspace concepts of operation such as flexibility and robustness. Evaluation *methods* are developed as appropriate to the novel concepts of operations being examined. For example, to properly compare a range of loci of control, a common (or operating from common principles) conflict detection and resolution (CD&R) algorithm is used which is then employed centrally or de-centrally according to the concept of operation. Finally, the *simulation platform* used for *analyses of specific concepts* (employing the evaluation methods to gather the desired metrics) is developed and configured. This thesis used the 'work models that compute' simulation engine (WMC).

2.1 Defining Airspace Essentials

There are a few core aspects that any airspace concept must have to safely provide for the transport of aircraft. Safety is obtained through separation assurance and collision avoidance, transport by trajectory determination, and fairness assurance establishes the priorities by which aircraft are granted air navigation services and access to the airspace. These three aspects, separation assurance, trajectory determination, and fairness assurance, are the minimum necessary aspects an airspace model must have to attain the goals outlined above. This thesis focuses primarily on the second of the aspects, trajectory determination, while accounting for constraints established by fairness assurance and safety.

Trajectory determination is the processes of selecting a path to travel through the airspace and is primarily performed by the users of the airspace. Sometimes this is as simple as plotting the shortest distance between two points, and sometimes it is a very involved process involving many waypoints and other restrictions. Trajectory determination also involves adapting the path to unexpected events such as weather or traffic. The locus of control is a major influence as to whether the trajectory determination is done in the cockpit of an individual aircraft (decentralized) or on the ground (centralized).

Separation assurance regulations come from the governing bodies of the airspaces (such as the FAA) and can be viewed as a constraint for the novel air traffic environment. The act of providing collision avoidance can be implemented in dedicated tactical systems and assumed to occur reliably at a finer spatial and temporal resolution than will be analyzed in this thesis. Thus, this study addresses separation assurance by establishing trajectories that nominally meet separation assurance constraints defined by ‘conflict’ boundaries.

Assuring fairness in the airspace is also the duty of airspace governing bodies, is a constraint in novel airspace concepts, and is considered in future work in areas such as game theory. Airspace fairness is the absence of bias toward one aircraft or group of aircraft with regard to air traffic control. As an example, an idea to help assure fairness would be to mandate certain control paradigms in certain areas, such as requiring completely centralized control in terminal areas, so that aircraft aren't competing (and potentially gaming the system) for arrival and departure slots.

2.2 Metrics

The *flexibility* of the airspace at periodic points in time is measured by aggregating the maneuverability (allowable trajectory change without causing a conflict) of every aircraft in the airspace at that time. The values can then be compared between each locus of control to compare their flexibility. These values can also be averaged over time to arrive at a single value (note, however, this single value may give little insight into the locus of control effects when the locus of control is dynamic and allowed to change within a scenario).

Assessment of the *robustness* of the airspace compares metrics of the control paradigms in nominal versus unplanned external disturbances (off-nominal conditions) such as weather, temporary restrictions, and anomalous aircraft (such as medevac and aircraft with degraded capability). Robustness can be measured by comparing any of the metrics assessed in nominal conditions with the same metric assessed in off-nominal conditions.

Measures such as arrival time, cruising speed/altitude (corresponding to fuel burn and monetary costs), etc. can be used to assess the *performance on a per-aircraft basis* of each control paradigm. Likewise, the *performance of the airspace* can be assessed. Some airspace measures can be assessed by aggregating the per-aircraft measures appropriately (i.e. time-weighted average). Additional metrics of airspace concepts include measuring the number of conflicts and losses of separations that occur.

2.3 Novel Air Traffic Management Operational Concepts

An air traffic management operational concept is a descriptive method for routing traffic though an airspace with the airspace essentials mentioned previously: safety (separation assurance), trajectory determination, and fairness assurance. Specifically, it encompasses the rules, regulations, and standard operating procedures applied to achieve the essential goals (and any additional goals) of that airspace. For instance, in en route airspace, if the trajectories of two aircraft conflict (meaning if their intended routes are predicted to result in a loss of separation at a future time), one operational concept may state that the appropriate central controller must command one or both aircraft to maneuver in order to resolve the conflict while another may state that the pilots of the respective aircraft must resolve the conflict themselves. A concept of operation would also define what maneuvers should be performed (in nominal situations) and how.

The operational concepts for a novel air traffic management environment may include substantial changes from the current day, including the absence of airspace classifications, clearances (except for required constraints such as restricted airspace), and flight plans. Figure 2 shows an example of a notional airspace example with a centralization mandate zone (the circle), a restricted zone, and multiple aircraft under different control paradigms.

The locus of control must be determined for each of the essential airspace functions noted earlier. Examining trajectory determination, for example, with a centralized control paradigm, each aircraft's trajectory is potentially dictated by a centralized controller provided by the air navigation service provider (ANSP). With decentralized control, trajectories are fairly free to be determined by users of the airspace (such as pilots or airlines) without being subject to as many constraints (some restricted areas may still be present) or modification by authorities both beforehand and while en route. In addition to fully-centralized and fully-decentralized concepts of operation, some concepts of operation may adjust whether each aircraft's trajectory is determined centrally distributed based on the aircraft's equipage and on desired user cost inputs (delay and fuel).

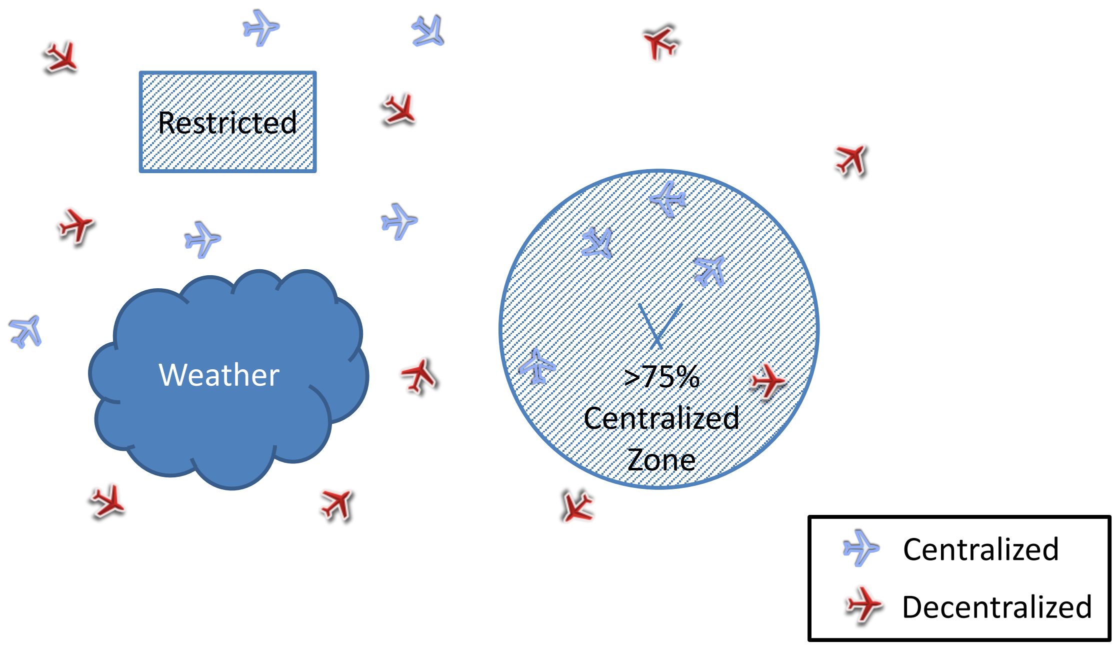


Figure 2 Notional airspace example

2.3.1 Evaluation Methods

To properly compare novel air traffic management concepts of operation, the same set of desired metrics must be collected for each concept in a manner that removes confounds from their comparison. For instance, with locus of control testing, it is of utmost importance that the conflict detection and resolution (which includes trajectory determination) algorithms be the same (or as common as possible) between the various control paradigms. This is because algorithms that are better suited for one control paradigm may skew the resulting metrics, leading to false conclusions about the effect of locus of control on airspace metrics of interest. Furthermore, since robustness is a metric, the evaluation method must be able to identify off-nominal or disturbance cases that may potentially exercise any of the concepts of operation in significant ways.

The model of the desired airspace must have a level of fidelity appropriate to assess the metrics. A necessary requirement of the airspace model includes the ability to modify the controlling entity of each aircraft, allowing for each aircraft to detect and resolve conflicts as well as be capable of receiving and complying with conflict resolution commands as shown in Figure 3. Specifically, each individual aircraft needs to be able to receive and comply with trajectories determined by a centralized controller and, in decentralized operations, determined their own conflict-free trajectory. Furthermore, they need to be able to toggle between centralized and decentralized control (if applicable) and optimize (if allowed) and fly their individual trajectories. The ground segment of the model needs to be able to detect all aircraft in the applicable airspace as well as be able to transmit conflict resolution commands. To resolve inter-control-paradigm conflicts, a right-of-way scheme must be established for all aircraft based on a number of factors including equipage or geographical area (i.e. some areas of the airspace could have a centralized right-of-way scheme while others might have a decentralized scheme), which is an aspect of fairness assurance.

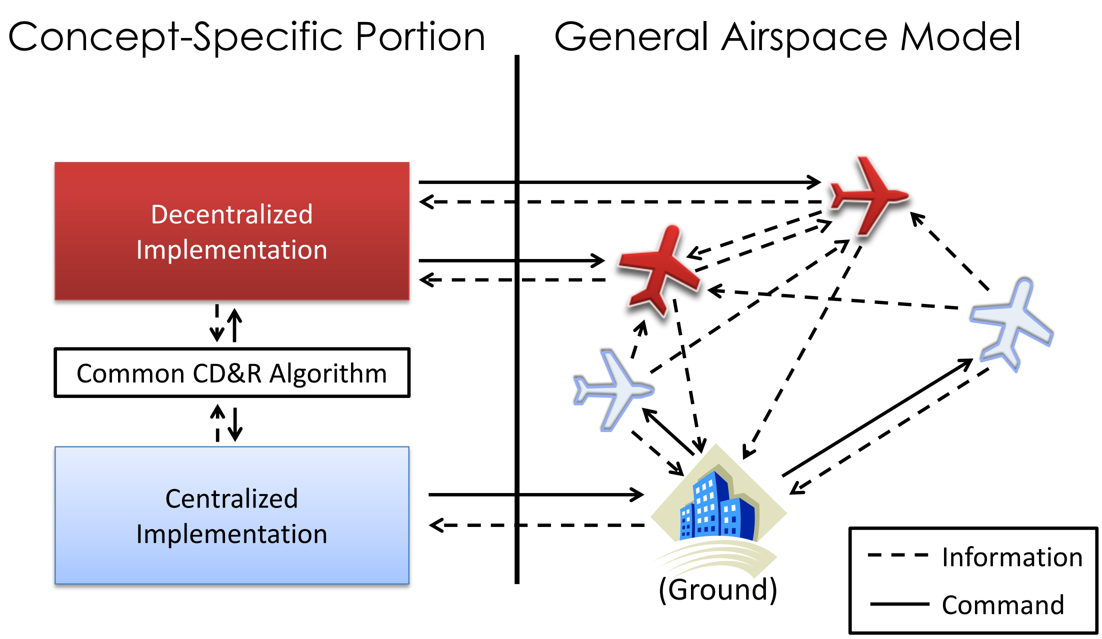


Figure 3 Locus of control comparison

CHAPTER 3

ANALYSIS OF SPECIFIC CONCEPTS

Analysis of specific concepts is demonstrated in this thesis by examining a range of locus of control concepts of operation. As shown in Figure 4, a number of experiments are possible within this framework and evaluation method. Specifically, this thesis illustrates an experiment design using a 'wagon wheel' approach and consists of two main parts: a full-factorial design of experiment matrix considered the 'hub experiment', and several further exploratory offshoots that serve as spoke experiments.

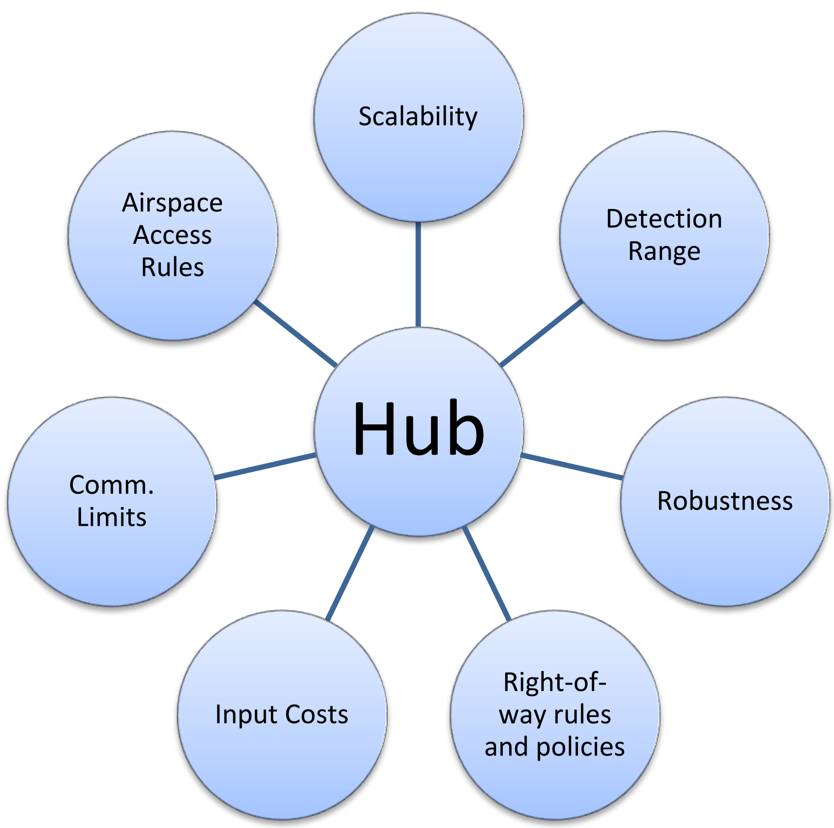


Figure 4 'Wagon wheel' experimental design approach

These experiments represent the range of factors affecting the locus of control in a variety of traffic situations. This chapter first describes the output metrics. Then the experiment design is provided for the ‘hub experiment’, and then a range of possible ‘spoke experiments’ are documented. The simulator configuration is discussed briefly followed by the tools necessary to perform the experimental runs.

3.1 Metrics

Building on the conceptual discussion of metrics given in 2.2, the *flexibility* of the airspace is specifically measured in one minute intervals by first assessing the maneuverability (allowable trajectory change without causing a conflict) of every aircraft in the airspace in three dimensions: heading, ground speed, and vertical speed. The allowable maneuvering in each dimension is normalized by the total range of that dimension based on a performance model for each aircraft (see section 3.5.3) at that particular point in time and space, indicating the percentage of the aircraft’s maneuvering that the airspace will allow in each dimension. The percentages in each of the three dimensions are then equally averaged to produce the overall flexibility value for each aircraft at that point in time. The airspace flexibility is calculated by equally averaging the flexibility of each aircraft at every sampled point in time and then integrating over time to arrive at a single value for the total flexibility of the airspace for a particular simulation run.

The *robustness* of the airspace requires the control paradigms to be evaluated in both nominal scenarios and those with unplanned external disturbances (off-nominal conditions) such as weather and anomalous aircraft (such as medevac aircraft that require priority). Robustness is measured by comparing any of the metrics in nominal conditions with the same metric in off-nominal conditions.

Measures such as delay (difference between actual end time and original end time for each aircraft to exit the airspace), fuel burn (calculated using aircraft performance models (see section 3.5.3)), and number of maneuvers performed (deviations from the original flight plan) are used to assess the performance of each control paradigm on a per-aircraft basis. Likewise, the performance of the airspace is assessed. Some airspace measures are assessed by aggregating the per-aircraft measures. In addition, safety implications of the airspace concept are examined by measuring the number of conflicts and losses of separation that occur.

Although actual cost (both per-aircraft and airspace aggregate, calculated from a combination of fuel burn and delay, each weighted by a cost index) is available, it was not used here because the fuel was calculated by estimating the fuel burn of the original flight plan and scaling it according to deviations from this flight plan commanded in the airspace. This was found to have some inaccuracies because no actual fuel data was available for the original flight plan. Thus, an estimated cost is used, as described in section 3.5.5. The same type of calculation is used to determine the lowest cost flight plan within a set of possible conflict resolutions and is used to aggregate an overall airspace value.

3.2 Hub Experiment

The 'hub experiment' examines a full-factorial experiment design with three dimensions: airspace scenario, ratio of aircraft under centralized or decentralized control, and look-ahead time for conflict detection and resolution (CD&R), as shown in Table 1. Each unique combination of levels within these three factors was tested in a set of five equivalent airspace scenarios (described in section 3.4).

Table 1 Hub run summary

Axis	Title	Runs	
1	Scenario	**5**	
2	Locus of control	**5**	
2.1	Completely centralized		1
2.2	Mixed centralized and decentralized (25%, 50%, and 75%)		3
2.3	Completely decentralized		1
3	CD&R Look-Ahead Time	**5**	
3.1	Finite time (2, 5, 10, and 30 min)		4
3.2	Infinity		1
	Total:	**125**	

3.2.1 Ratio of Aircraft under Centralized or Decentralized Control

Every aircraft was under either centralized or decentralized control, with the assignment for each aircraft chosen ahead of time and constant throughout each run. The ratio of aircraft under centralized or decentralized control is a percentage (0-100%) of the number of aircraft under decentralized control: a value of 0% indicates all aircraft are under centralized control whereas a value of 100% means all aircraft are under decentralized control. Ratios evaluated in the 'hub experiment' were 0%, 25%, 50%, 75%, and 100%.

For the cases between the extremes of 0% (fully centralized) and 100% (fully decentralized), a right-of-way rule is used to determine which aircraft has priority in a conflict between centralized- and decentralized-controlled aircraft. When resolving conflicts in general, the locus of control type (centralized or decentralized) that has right-of-way will not take into account aircraft of the non-priority locus of control type. This means that the aircraft that have right-of-way may cause new conflicts that the aircraft that do not have right-of-way will need to resolve. The 'hub experiment' examines only the situation where centralized-controlled aircraft have the right-of-way.

3.2.2 CD&R Look-Ahead Time

The look-ahead time is temporally how far along the flight plan of each aircraft the CD&R algorithm can look to both detect and resolve conflicts. This value can vary from 0 seconds to infinity. To include all aircraft that could conflict with aircraft currently in the airspace, the future flight path of aircraft that are not yet in the airspace are also examined, but an aircraft's flight plan is not modified unless it is in the airspace at the time a conflict is detected. Thus, aircraft in the airspace may have to maneuver to resolve a future conflict with an aircraft not yet in the airspace. The values for CD&R look-ahead time for the hub experiment were 2, 5, 10, and 30 minutes, and infinity. Functionally, within the CD&R algorithm, a look-ahead time of 300 minutes effectively represents infinity within the four hour simulation runs examined here.

3.3 Spoke Experiments

The framework and analysis methods defined in Chapter 2 also allow for several different factors of locus-of-control to be examined in more detail in 'spoke experiments.' These extend from the full-factorial design of the hub experiment with partial factorial designs that target interesting factors within the essential airspace aspects of trajectory determination and fairness assurance (note, a fixed definition of 'conflict' maintains a constant representation of the essential aspect of safety throughout). This section will describe how spoke experiments could evaluate factors such as scalability, detection range, robustness, right-of-way rules and policies, costs, communication limits, and airspace access rules.

3.3.1 Scalability

The aircraft traffic density is defined in terms of a traffic multiplier. This multiplier is in reference to an initial traffic data set input or airspace scenario (see section 3.4). For instance, a 1x multiplier implies that all and only the traffic from the initial data set is used whereas a 2x multiplier implies that additional set of traffic, equal to the size of the original traffic set, is added to the original traffic set using a predictable traffic multiplier (see section 3.5.4). The scalability spoke experiment iteratively homes on the traffic density, reflecting the capacity limit (ideally) of each control paradigm. The number of unresolved conflicts is expected to increase exponentially at some point, resulting in many losses of separation and/or an increased number of maneuvers, reflecting large decreases in airspace performance. The capacity limit will seek to identify and characterize this inflection point in the relationship between traffic density and performance.

3.3.2 Detection Range

This 'spoke experiment' examines where the look-ahead time, as driven by the range between aircraft at which conflicts can be detected, begins to produce diminishing returns in terms of aircraft and airspace performance. If the range is too small, aircraft have to be more agile in terms of immediate, large maneuvers at the potential expense of fuel and time; if the range is too large, aircraft can be more strategic, yet may still need to make sudden changes when responses to, say, a new aircraft entering the airspace near them or another nearby aircraft suddenly changing its flight plan effectively negate their strategic flight planning. Therefore, there may be an optimal range somewhere between these extremes. In addition, detection can be varied from 'no future' (where aircraft entering the airspace in the future are not considered), 'see future' (where aircraft entering the airspace in the future can be seen but not manipulated) and 'move future' (where aircraft entering the airspace in the future can be seen and their flight plans can be modified now to prevent conflicts in the future).

3.3.3 Robustness

The robustness 'spoke experiment' compares runs in nominal scenarios with those same runs with off-nominal events. Medevac aircraft (or other high-priority aircraft) can be represented by allowing an aircraft to always have right-of-way or priority over all other aircraft. This means that the centralized and decentralized controllers will not modify the flight plan of these aircraft to help resolve conflicts. In addition to medevac aircraft, isolated convective weather systems are modeled as an "aircraft" with a large separation radius (equal to that of the weather) with a very slow speed. Fronts are modeled as multiple aircraft appropriately temporally spaced with large overlapping separation radii following the same flight plan, moving slowly. The metrics assessed in these off-nominal runs is compared to the performance of the same nominal versions of each run and their difference provides an assessment of robustness.

3.3.4 Right-of-way Rules and Policies

As described in section 3.2.1, when there exists a mix of centralized- and decentralized-controlled aircraft, a right-of-way rule is needed to determine which aircraft have priority. This 'spoke experiment' examines the effects of the right-of-way rule by adding additional runs with decentralized-control aircraft having priority (for comparison to runs in the 'hub experiment' that were identical except that centralized aircraft had priority). Furthermore, it examines the effects of the following control policies (which relates to the airspace essential aspect of fairness) for resolution of conflicts between centralized- and decentralized-controlled aircraft:

1) When a control paradigm is *greedy*, it seeks to find the absolute lowest cost conflict resolution with no regard to aircraft that do not have right-of-way. This means that one aircraft's conflict resolutions could create conflicts for aircraft that do not have right-of-way. Even with a greedy algorithm it is possible that no conflict-free resolutions can be found, which also should be recorded.

2) In *accommodating* mode, the CD&R implementation first computes the cost of a resolution while considering the aircraft that do not have right-of-way. If conflict-free resolutions can be found, then the lowest cost of those resolutions is used. Otherwise, resolutions resort back to being greedy and are recomputed without considering aircraft that do not have right-of-way and the lowest cost of these resolutions is then used. As before, it is possible that no conflict-free resolution can be found; thus it is recorded whether an accommodating, greedy, or no resolution was found.
3) Finally, in *considerate* mode, the controller computes a resolution while considering aircraft that do not have right-of-way. The lowest cost of these resolutions is used. Once again, it is possible that no conflict-free resolution can be found; again, in this case that information is recorded.

3.3.5 Cost

The cost 'spoke experiment' has two aspects which both examine the cost index considered in trajectory determination, i.e. the relative weighting between fuel and delay. First, the cost index considered in trajectory determination can be explored with at least four settings: mixed (where each aircraft has its own cost index), uniform (where all aircraft have the same cost index), active average (where the average cost indices of each active aircraft in the airspace is used in determining all aircraft trajectories), and full average (where the cost indices of all aircraft ever to enter the airspace are averaged). Thus, this aspect explores the impact of the ability to allow for changing even individual cost indices versus a fixed cost index inherent in trajectory determination within CD&R. Second, the effects of different cost indices per aircraft in each of the aforementioned cost modes can also be examined for their impact on the metrics of air traffic concepts of operation.

3.3.6 Communication Limits

Bringing the simulation closer to realistic situations, communication limits can be imposed in many ways for both centralized and decentralized aircraft. Decentralized aircraft may have an ADS-B range (e.g. 100% at 90nmi) that does not allow for knowledge of the intent of every aircraft in the airspace. This differs from the construct of look-ahead time, which assumes knowledge of all aircraft but elects to resolve only conflicts falling within a given look-ahead time. Instead, the communication limit recognizes that flight plans from individual aircraft that are outside the ADS-B range are unknown to the ownship aircraft, regardless of when they may cause a conflict. Centralized communication limits may include data throughput limits and/or integrity issues that limit the number of (or rate of) ground-to-air and air-to-ground communications and/or that corrupt some of the communications so that a re-transmit is necessary. Another way to add real-world effects into both the centralized and decentralized communication systems is to add errors in broadcasts of navigation data and estimated time of arrival at fixes along the flight route, simulating real-world uncertainties in navigation and surveillance.

3.3.7 Airspace Access Rules

Another aspect that could be examined concerns airspace access rules. This can include something like allowing aircraft to enter the airspace only where it impacts the complexity or maneuvering required within the airspace the least. To accomplish this, a tool called a ‘complexity map’ (see Figure 5 for an example) can be used to determine where and when the best entry point would be, or points where entry may not be allowed [19]. Airspace access rules also relate to the essential airspace aspect of fairness, as policies may be explored for allowing aircraft to enter airspaces only at points (and with a heading or flight plan) where the complexity they add to the airspace is below a certain threshold.

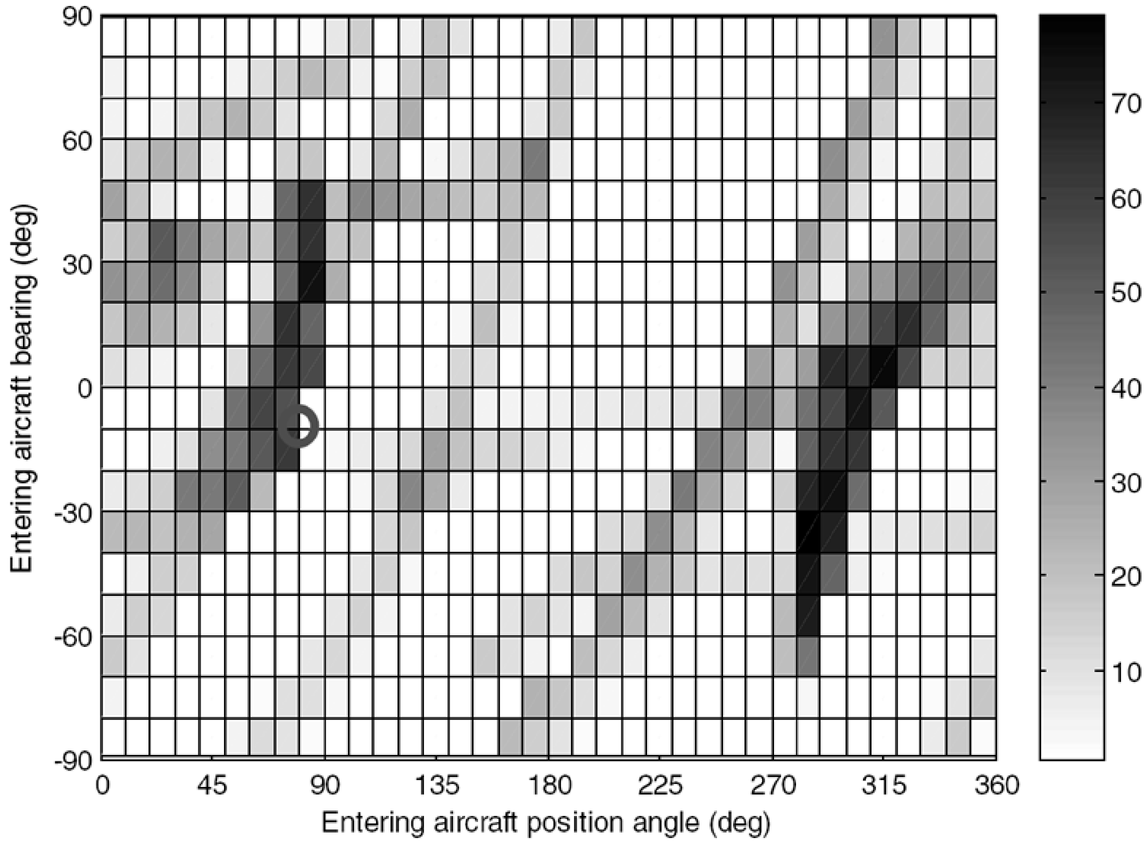


Figure 5 Complexity map example [19]

3.4 Simulation Configuration and Scenarios

Simulations are configured by several factors including the traffic scenario, traffic volume, percentage of the aircraft that are under decentralized control versus centralized control, which control paradigm has the right-of-way, the percentage of cost that the centralized control paradigm is for fuel (versus delay), the decentralized control paradigm cost mode (uniform across all aircraft, mixed between aircraft, averaged across all active aircraft, or averaged across all aircraft in the scenario), and the cost index for the airspace (if in uniform cost mode) or for each aircraft.

For the traffic scenarios, each aircraft has a unique name, aircraft type (indicating its performance class), and two numbers that are assigned randomly beforehand and used to determine its locus of control and cost index. Each aircraft is also linked to a list of 4D waypoints that serves as its initial flight plan. Although an unlimited number of waypoints may be assigned to an aircraft, in these experiments only two were used: one for the airspace entry and one for the exit. The initial aircraft data is taken from ETMS center boundary crossing data, isolating the Indianapolis center, identifying aircraft starting and/or ending at or above 18000ft, and comprising five hour segments (the first hour is used to initialize the simulation). The data is specifically between the hours of 1pm and 6pm EDT on each of July 4th-8th, 2005.

3.4.1 Ensuring Flight Plan Feasibility

Because the traffic scenarios utilize only ETMS start and end points, the intermediate aircraft trajectory is discarded and is assumed to be a straight line between the two points. However, most aircraft cannot actually perform in this manner, especially if the flight plan involves a climb or descent or the time between the start and end points is long (because, for example, the actual flight plan included a holding pattern or significant lateral maneuvering), resulting in a low airspeed. Also, the CD&R algorithm used here was not designed to work with flight plans whose legs have varying speeds. Therefore, additional waypoints may need to be added to create initial flight plans accommodating both aircraft performance and the capabilities of the CD&R algorithm.

First, the aircraft performance limits are checked: if a direct path requires, at the start or end points, speeds (or vertical speeds) outside the aircraft's performance limits (as defined by the greatest and least velocity, and greatest and least vertical speed possible at both points), the end point time is adjusted in an attempt to make both points feasible. Next, if the flight plan does not fit within the aircraft's normal performance envelope, additional waypoints are added (by dividing the flight plan evenly by 2, then 3, 4, etc.) and the altitudes and times at each waypoint are adjusted through a set number of iterations. The flight plan division occurs until either a solution is found or the waypoints are less than 30 seconds apart. If a solution cannot be found (or the altitudes are too high for the aircraft performance), the flight plan and associated aircraft are removed from the traffic scenario as an outlier. Finally, any aircraft starting or ending below 18000ft have their flight plans cut off at 18000ft and the lower portion removed.

3.4.2 Simulation Initialization and Grace Periods

To record a realistic traffic situation, the simulation is initialized by running for one hour of simulation time, at which point the airspace is fully and realistically populated, and then data is recorded for the subsequent four hours. To be counted in the airspace metrics, aircraft must finish their flight plans within the four hour data collection window and any conflicts or losses must have been detected and/or have an end time (the time at which separation is regained) that resides inside this window.

Also, each aircraft has a grace period of 2 minutes after the start of its flight plan and 2 minutes before the end of its flight plan. During this grace period, no conflicts or losses count toward the airspace statistics. This helps greatly reduce any unresolved conflicts and/or losses arising from fixed starting and ending points. The grace period also corresponds to the CD&R algorithm used here placing a waypoint 1 minute 'lead-in time' along the flight plan starting from the aircraft's current position as a 'maneuvering' point before it can add or change any other points, and then using a default climb/descent rate of 1500 ft/min relative to a minimum altitude separation of 1000ft (yielding less than a minute necessary to climb to avoid a conflict). The 1 minute 'lead-in time' comes from a maximum lateral maneuver being 90 degrees given the standard turn rate for aircraft at higher speeds (greater than 250 knots) being 1.5 degrees per second.

3.5 Simulation Tools

Several tools are needed for these simulations. These tools include: WMC, or Work Models that Compute, as the simulation platform; an outer loop aircraft dynamics model with flight plan following for the simulation of aircraft following a flight plan; BADA, an aircraft performance database; a predictable traffic multiplier that enables the generation of large, repeatable, traffic densities; a flight plan cost calculation function that enables comparison of new flight plans arising from conflict resolution; and StratWay, a CD&R algorithm that determines conflict-free trajectories with centralized and decentralized implementations. Figure 6 depicts the relationships between those tools and the following sections detail each.

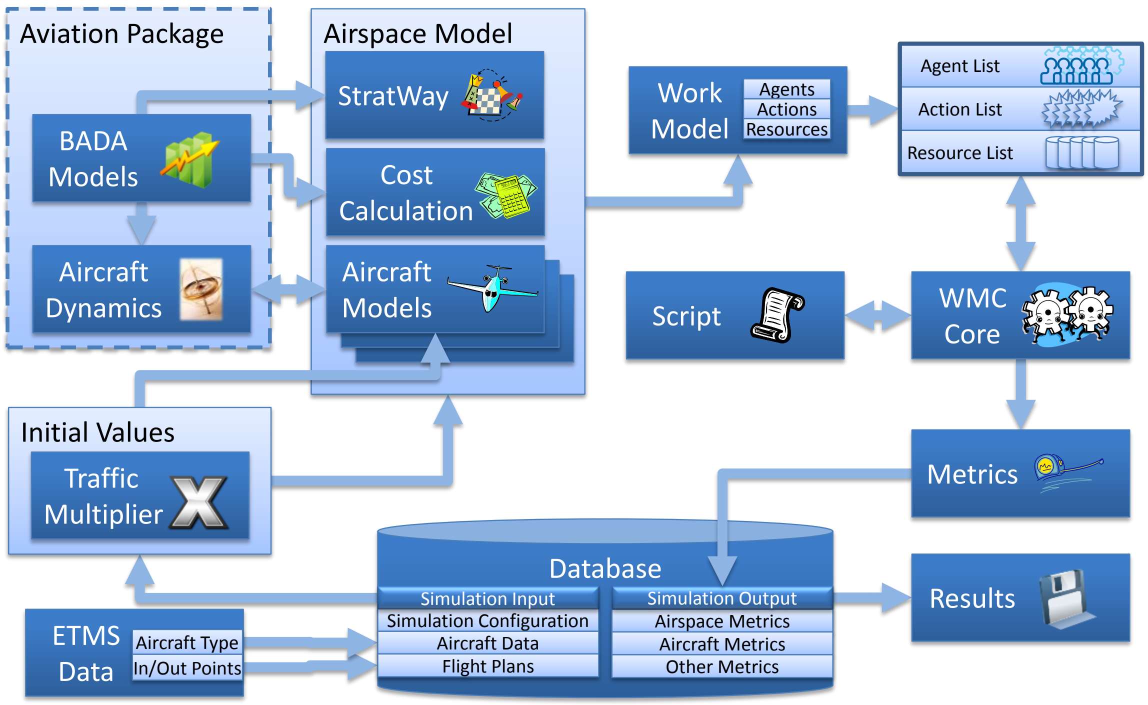


Figure 6 Simulation component block diagram

3.5.1 Simulation Platform: WMC

WMC is a simulation engine under development at Georgia Tech for analyzing complex systems and understanding both local behavior of system components as well as system-wide emergent behaviors. The platform builds on models of agents, the actions they perform, and the resources actions 'work' on. Models of actions and resources are allowed to take on a range of forms, allowing for models approximating both continuous-time and discrete-event dynamics within system components. Performance modeling in the agents allow for the introduction of elements such as human characteristics into the system. Continuous dynamics of physical systems can be achieved through static or dynamic update times.

3.5.2 Outer Loop Aircraft Dynamics Model with Flight Plan Following

An outer loop aircraft model follows the flight plans originally given to each aircraft as well as the ones generated from conflict resolutions. An outer loop model is a relatively simple point-mass aircraft dynamics model that, for this experiment, uses first-order controllers to directly regulate eight states: latitude, longitude, altitude, true airspeed, thrust, roll, heading, and flight path angle. Course tracking is provided by a simple waypoint following algorithm that takes into account turn radii. A more complex speed controller is necessary to arrive at the next waypoint on time yet travel at the current leg's speed if a previous leg was at a different speed. This controller first sets the throttle to full if the aircraft is too slow or to idle if too fast. Then, the approximate acceleration rate is measured from this change in speed and used to calculate when the throttle needs to be set in the extreme opposite direction once the speed has crossed the desired speed value. Once all this happens, the aircraft is put back into true airspeed control mode to resume the desired speed. The goal of this complex speed change is to compensate for the lack or excess of speed as quickly as possible to reduce flight plan following error.

An outer loop model is chosen for its relative dynamic simplicity in order to reduce simulation runtime. A fifth- and sixth-order Runge-Kutta-Fehlberg (RKF56) method is used to integrate the differential equations with an adaptive timestep; thus it reports its next update time to WMC as a discrete event in WMC at the current simulation time plus the timestep. Finally, aircraft performance values are calculated using Eurocontrol's BADA performance models, described in next section 3.5.3.

3.5.3 Aircraft Performance and Fuel Models (BADA)

BADA (Base of Aircraft DAta) is a database of aircraft performance values that can be used to model aircraft performance profiles throughout all flight regimes [21]. The performance values given for each available aircraft type include thrust, drag, and fuel coefficients as well as weights, speeds, and maximum altitudes. These values can be used with the so-called Total Energy Model (TEM), a reduced point-mass model relating thrust, drag, acceleration, velocity, and vertical speed of an aircraft, to create aircraft performance profiles. Additionally, performance profile information can be interpolated and extrapolated from provided nominal performance look-up tables. BADA also provides files for each available aircraft that describe the default operational climb, cruise, and descent speed schedules most likely used by airlines. Finally, since BADA spans a reduced set of aircraft types, a synonyms file is included that matches most commonplace aircraft with similarly-performing aircraft available in BADA. This experiment uses the TEM to calculate all performance values from basic principles and provide these aircraft coefficients to the outer loop aircraft dynamics models to parameterize each according to its aircraft type.

A performance check function uses BADA performance data to determine if a flight plan corresponds to feasible altitudes, speeds, and vertical speeds for a particular aircraft. This function is used alongside the flight plan feasibility assurance function noted in section 3.4.1 and for checking the feasibility of new flight plans generated by the CD&R algorithm. It works by looping through each flight plan leg, determining the speed and vertical speed necessary to fly each leg, and checking whether those values are within the aircraft's capability at the altitudes on either side of each leg and the speed of the leg. If any of the legs are outside of the aircraft's performance capability, the flight plan is rejected.

3.5.4 Predictable Traffic Multiplier

A predictable traffic multiplier is necessary to establish desired traffic density levels. It must be predictable so that each run, given the same input traffic (described in section 3.4) and the same multiplier, applies exactly the same traffic set every time. In order to be predictable, no randomness can be used unless it is repeatable such that it produces the same results with the same input traffic and multiplier. The traffic multiplier must also include the original input traffic in the output traffic set if the multiplier is greater than one or a subset of the input traffic if the multiplier is less than one. The input traffic set is not modified if the multiplier is equal to one. Finally, the traffic multiplier must produce additional aircraft (if requested) that mimic the initial positions and routes of aircraft in the input traffic while trying to avoid starting aircraft in positions that are already in loss of separation or will be soon.

The predictable traffic multiplier first loops through every aircraft in the input traffic set and, for each source aircraft, builds a list of every other aircraft's flight plan start and end points ranked according to spatial proximity (lowest is first). It then loops through this list and attempts to add (if necessary) a candidate aircraft positioned at least twice the minimum separation distance (10nmi laterally or 2000ft vertically, whichever is the dominant direction) from the source aircraft (alternating between the direction towards the proximate aircraft and the opposite direction. If the candidate aircraft starting position is within twice the minimum separation distance and 3 minutes from another aircraft, the traffic multiplier will keep increasing the distance by twice the separation distance in the dominant direction away from the source aircraft until it has either reached half the distance to the next closest original aircraft or airspace and aircraft altitude restrictions have been violated (18000ft airspace floor, BADA aircraft performance maximum). For instance, if the source and next closest original aircraft are at the same altitude, the predictable traffic multiplier will first attempt to place the candidate aircraft 10nmi laterally from the source aircraft toward the next closest original aircraft, then

10nmi from the source aircraft in the opposite direction from the next closest original aircraft, then 20nmi in the direction toward the next closest original aircraft, and so on. If this is unsuccessful, the predictable traffic multiplier will move on to the next closest original aircraft and try again. If the list is exhausted, the unsuccessful source aircraft will be removed from the list and the predictable traffic multiplier will try again with the next aircraft in the list as the source aircraft.

Once a feasible starting position is found, the end point is determined using the same process as for the starting point except that it uses next-closest flight plan end points. The resulting flight plan is put through a performance check (described in section 3.5.3), flight plan feasibility insurer (described in section 3.4.1) if that fails, and another performance check, respectively. If all three of those items fail, the next-next-closest end point is used to attempt to find a new end point. If all proximate end points have been exhausted, the predictable traffic multiplier starts over to determine a new starting point, then proceeds again with attempting to find an end point. If all next-closest original aircraft and end point combinations have been tried with no success, the source aircraft is removed from the list as before and the process starts over. If all source aircraft are removed from the list before the necessary quantity of aircraft is produced, then the predictable traffic multiplier reports its failure. Note that this can happen only after $s * n^2$ combinations have been tried, where n is the number of aircraft in the input traffic set and s is the remaining source aircraft in the list (which starts at n).

The time of entry of each new aircraft is spaced between the entry time of the two aircraft that defined the location of its start point, starting at half-way between them. If the original aircraft pair spans a second aircraft, the denominator is multiplied by 2 and the numerator is set to 1; if it spans a third aircraft, the numerator is increased by 2; and so on. For instance, if two original aircraft produced three new aircraft, those new aircraft would be in temporal increments that are one-fourth the temporal distance between the two original aircraft with the first aircraft at 1/2, the second at 1/4 and the third at 3/4.

Each new aircraft inherits all the properties (locus of control, type, etc.) of the next closest (original) aircraft. The names of the new aircraft start with the original aircraft name and append sequential values for each new aircraft generated.

3.5.5 Flight Plan Cost Calculation

The flight plan cost calculation is used by both the centralized and decentralized CD&R implementations to assess the “goodness” of new trajectories generated to resolve conflicts. It assesses a flight plan (a vector of 4D waypoints) for a particular aircraft via a cost index that weights delay and fuel in the cost calculation. Delay is calculated simply by taking the time of the last waypoint in the flight plan and subtracting from it the time of the last waypoint in the aircraft’s original flight plan. Fuel is a more complex value calculated using aircraft performance and fuel burn data from BADA as well as the altitudes and speeds of each leg of the flight plan. A normalization factor for converting delay into fuel is calculated by determining the nominal fuel burn rate (using BADA) during cruise using the average altitude (of all the legs) and average thrust (once again, using BADA to calculate the drag for each leg) for the entire flight plan. Finally, a single value is returned for the given (conflict resolution) flight plan.

3.5.6 Conflict Detection and Resolution

The StratWay algorithm being developed at NASA Langley serves as the common CD&R algorithm. For conflict detection, it evaluates the predicted waypoints for an ‘ownship’ aircraft relative to the predicted waypoints of other ‘traffic’ aircraft. Several different path and time augmentation algorithms can be used to automatically adjust the future waypoints of the ownship aircraft to reduce or eliminate conflicts.

Although StratWay was designed be used to try to resolve, at the same time, all future conflicts for a given ownship aircraft, the usage here is on a more granular, per-conflict basis. This is achieved by limiting an aircraft’s detection and resolution look-ahead times to the end time of its next conflict. Say aircraft A is in conflict with aircraft B at time 1 and in conflict with aircraft C at a later time 2, which is still within the look-ahead time of all three aircraft. If aircraft A is used by StratWay as the ownship and thus required to resolve the conflicts, StratWay was originally designed to attempt to resolve both conflicts simultaneously. However, the overall cost may be lower to have either (or both) aircraft B or aircraft C attempt to resolve their respective conflicts with aircraft A. Thus, with this implementation, depending on right-of-way, priority, or cost, either aircraft A or aircraft B is called to resolve the conflict at time 1, and the end time of that conflict is used for both the detection and resolution look-ahead times within StratWay. Once the conflict at time 1 is resolved, either aircraft A or aircraft C is called (once again, depending on right-of-way, priority, or cost) to resolve the conflict at time 2, and the end time of that conflict is used for both the detection and resolution look-ahead times within StratWay.

When conflicts are unable to be resolved (sometimes after multiple attempts, as described in the next sections), they are marked as unresolved so that they are not addressed again. In the previous example, if the conflict between aircraft A and aircraft B at time 1 was marked as unresolved (and aircraft A attempted to resolve it, possibly in addition to aircraft B) and aircraft A was called to resolve the conflict at time 2 with aircraft C, StratWay would not be able to return a conflict-free conflict resolution flight plan because the conflict at time 1 was still unresolvable. This means that the conflict at time 2 could potentially be marked as unresolved due solely to the conflict at time 1 being unresolved. In order to overcome this, a rechecking mechanism was employed. This mechanism is scheduled to occur after the soonest unresolved conflict involving each aircraft. Continuing with the above example, right after the end time of the conflict at time 1, aircraft A (and aircraft B) would recheck for conflicts without ignoring conflicts marked as unresolved (in this case, the conflict at time 2). Therefore, the conflict at time 2 would then be available for attempted resolution without the unresolvable conflict at time 1 tainting StratWay's conflict resolution flight plans.

Centralized- and decentralized-control require different implementations of when StratWay is applied, how many aircraft it considers (for both the ownship and traffic), and how the flight plan cost calculation function is used when resolving any pair of conflicting aircraft trajectories. These implementations provide the interface between the aircraft and the CD&R algorithm as established by the locus of control of each aircraft.

3.5.6.1 Centralized Control Using StratWay

A perfect centralized controller would simultaneously solve all conflicts in the airspace and determine the "best" resolution by moving the appropriate aircraft: sometimes both aircraft involved in a conflict should be moved, and sometimes other aircraft must also be maneuvered too. The implementation used here mimics this by creating a tree of all possible combination of conflicts, aircraft, and resolution strategies. It starts with a list of conflicts that require a centralized-controlled aircraft to maneuver and calculates a total cost for all their current flight plans. Then, for each centralized-controlled aircraft, it attempts every possible resolution strategy. For the resolution strategies that produce a conflict-free solution and pass a performance check (section 3.5.3), a cost is calculated for the new flight plan and substituted for the cost of the old flight plan in the total cost, and then the centralized implementation examines a list of conflicts that excludes the previous conflict. This cycle continues until the list of conflicts becomes empty (see Figure 7). Once this happens, if the new solution has a lower total cost than the previous solution (if one exists), the new solution becomes the best solution. If no complete solution is found, each conflict is marked as unresolved and the simulation continues. There is one exception when recursively iterating through the list of conflicts, however, where, if one of the aircraft involved in a conflict has not entered the airspace yet and the look-ahead mode is set to ‘see future’ (see sections 3.2.2 and 3.3.2), then that conflict is skipped if no resolutions are found.

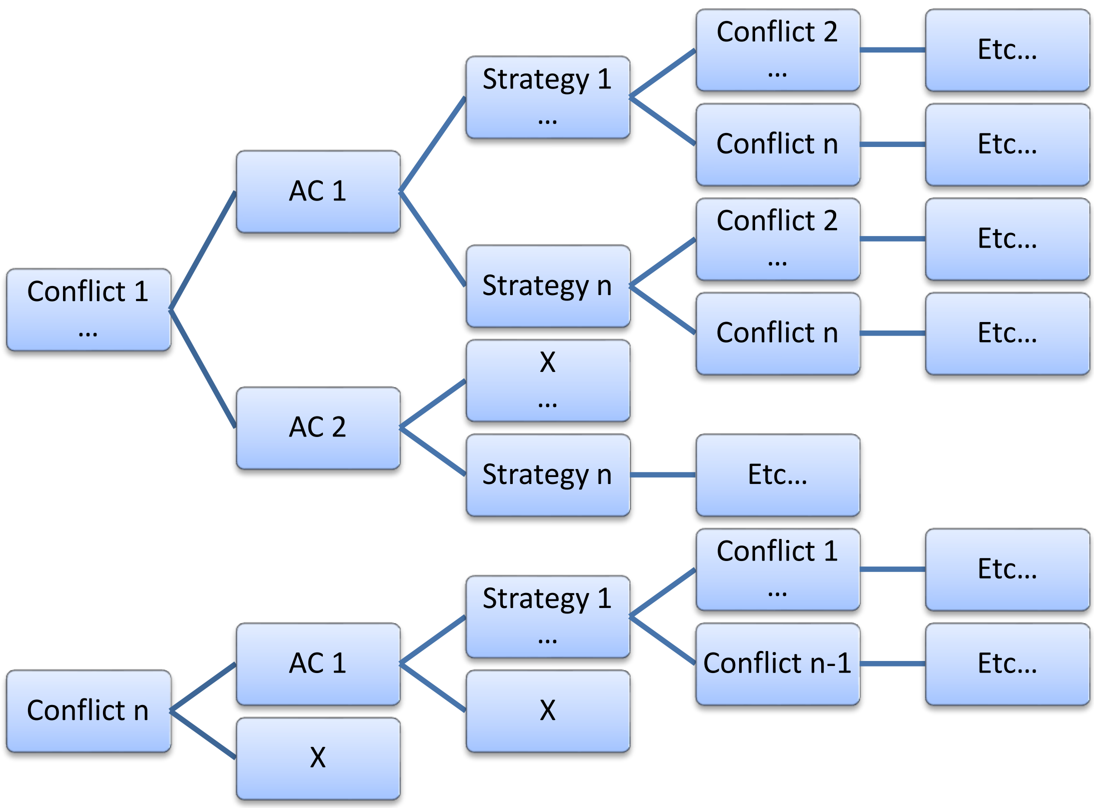


Figure 7 Centralized wrapper recursive tree. The X’s represent stopping points in the tree.

Although the number of conflicts to be evaluated is normally fairly small, a fully-centralized airspace with 3 conflicts and 29 strategies might have 195,112 (3 conflicts ^ (2 aircraft per strategy * 29 strategies)) possible solutions. Obviously the number of solutions grows exponentially with the number of conflicts. Therefore, tree pruning was added to make the centralized controller computationally tractable. The pruning terminates branches that have a cost that meets or exceeds the current best solution’s cost. This operates under the assumption that point-to-point (great circle) flight plans between the initial start and exit points into and out of the airspace are the lowest cost in terms of both delay and fuel usage. Although this assumption is not always correct for the traffic scenarios used here, the pruning has been found to find the best solution about 84% of the time, and a pretty good solution (<10 lbm cost difference from the optimal solution) about 10% the time. There are rare cases (about 6% of the time) that it finds a much worse solution, but over half of the CD&R calls complete on the average about 3 minutes faster (per call) than without pruning enabled.

3.5.6.2 Decentralized Control Using StratWay

The decentralized CD&R implementation loops though all conflicts, ordered ascending by time that require a decentralized-controlled aircraft to maneuver. If a conflict involves two decentralized-controlled aircraft, NASA's AOP (Autonomous Operations Planner) vertical and lateral priority rules are used to determine which aircraft has priority (and therefore the other is required to maneuver). The right-of-way rule determines which aircraft is required to maneuver when a centralized-controlled aircraft and a decentralized-controlled aircraft are involved. Once priority has been established, the aircraft that does not have priority attempts to resolve the conflict using all available strategies. The cost for each conflict-free resolution is calculated and the resolution with the lowest cost is chosen. If the non-priority aircraft is unable to find a conflict-free resolution using the available strategies, a resolution attempt action is scheduled for the priority aircraft from 2 minutes later (see primarily section 3.4.2 but 2 minutes is also the smallest look-ahead time used here) to 3 minutes later (NASA AOP procedure), depending on the look-ahead time (3 minutes later with a 2 minute look-ahead time would result in a loss of separation before the second resolution attempt was made).

Of the two aircraft in conflict, all the NASA AOP priority rules label one the traffic aircraft and the other the ownship aircraft. They all make conditional assessments that are measured at the point of first loss of separation. The vertical rules are evaluated first, followed by the lateral rules, if necessary.

For the vertical rules, if one of the two aircraft is descending (< -150 ft/min), then that aircraft has priority. If both are descending, the lateral priority rules are used next. If neither are descending, and one of the two aircraft is cruising (level flight up to and including 0±150 ft/min), that aircraft has priority. If both or neither are cruising, the lateral priority rules are used.

The lateral rules are divided into two main parts depending on whether it is a head-on conflict (ground track difference between aircraft is within and including 180º±5º). If it is, and the traffic is heading Westerly (225º < heading ≤ 315º), then the traffic has priority. If it's a head-on conflict and the traffic is heading Southerly (135º < heading ≤ 225º) and the ownship is heading Easterly (45º < heading ≤ 135º), then the traffic has priority. Otherwise in a head-on conflict the ownship has priority. If it's instead an overtake conflict (ground track difference between aircraft is within [but not including the extremes] 0º±5º) then the aircraft with the lowest ground speed has priority, with the ownship having priority if the ground speeds are equal. Finally, if it's not a head-on or overtake conflict, the traffic and ownship velocity vectors are placed head-to-head and the aircraft with the velocity vector on the right has priority.

CHAPTER 4

RESULTS

4.1 'Hub Experiment' Results

The 'hub experiment' was configured to examine the effects of a range of loci of control as well as CD&R look-ahead time on aggregate airspace metrics. The loci of control values used were from 0% decentralized (completely centralized) to 100% decentralized with three interim test conditions (25%, 50%, 75%) to simulate airspace with mixed operations. The look-ahead times included four finite values of 2, 5, 10, and 30 minutes with an additional time of 300 minutes (5 hours) to simulate an infinite look-ahead time. The simulation runs were configured with all possible combinations of these independent variables and ran with 5 different traffic scenarios for a total of 125 runs.

Aggregate airspace metrics such as flexibility, fuel and delay, percentage of conflicts that were unresolved and caused losses of separation, and cost were analyzed and are presented here. Most of these metrics are averages of the 5 scenarios. However, note that some of the results are very dependent on the number of aircraft, as well as the flight plans of the aircraft. The results have typically been normalized by an appropriate value, such as number of aircraft, but cases will also be noted where this does not always account for variations between traffic scenarios. Note that any graph interpolations (lines or surfaces) are purely for visual clarity and do not represent intermediate data points.

Figure 8 shows four views of a 4 hour time-lapse of the same traffic scenario with the flight plans (original and modified throughout the run) for a fully centralized run (top left), a 50% decentralized run (top right), a fully decentralized run (bottom left), and all aircraft positions at 1 minute intervals for the 100% decentralized run. The center boundary can be seen most clearly in the bottom right as a translucent white line whereas the grace periods (2 min) for each flight plan can be seen in solid white on each end of the flight plans. Note that any white appearing in the middle of the airspace indicates a descent or climb into or out of the airspace.

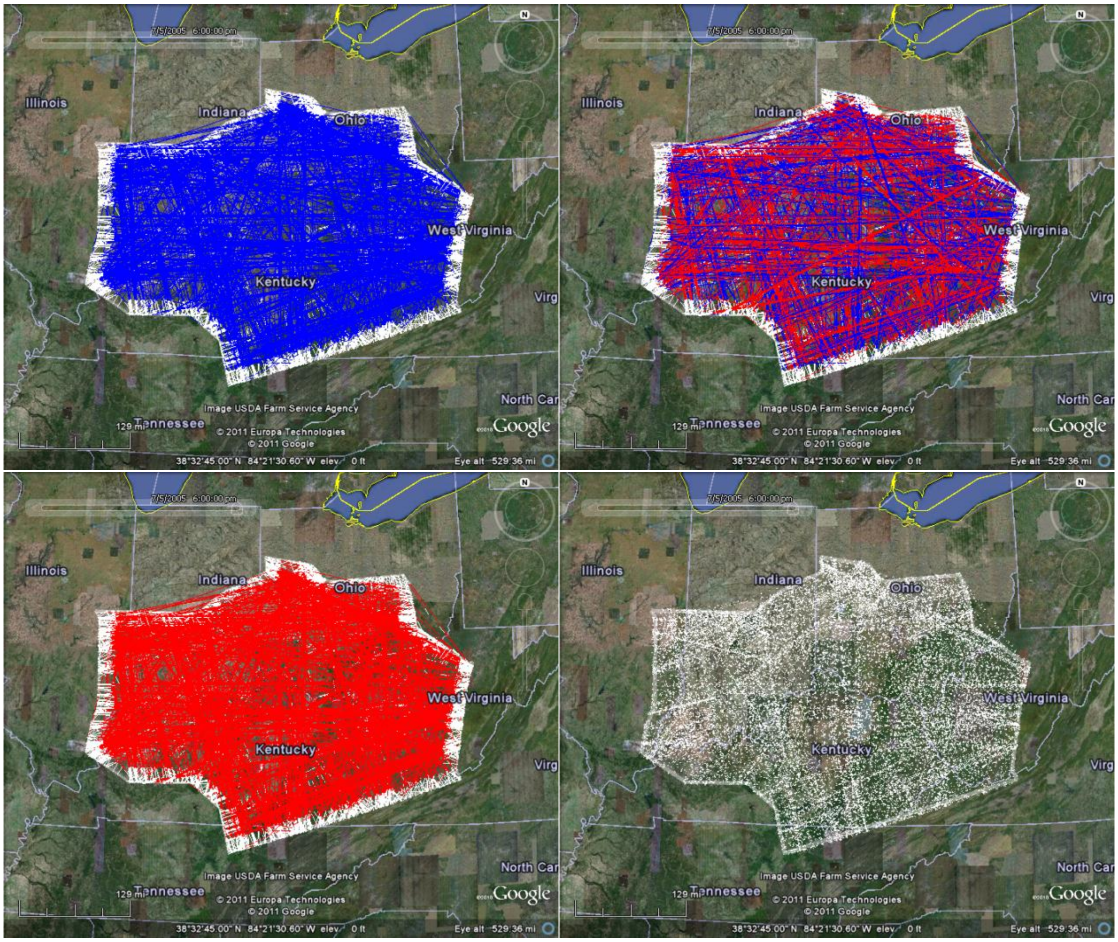


Figure 8 Four views of a 4 hour time-lapse of the same traffic scenario with the flight plans (original and modified throughout the run) for a fully centralized run (top left), a 50% decentralized run (top right), a fully decentralized run (bottom left), and all aircraft positions at 1 minute intervals for the 100% decentralized run

4.1.1 Flexibility

The flexibility of the airspace (section 3.1) is shown in Figure 9 as a function of look-ahead time and percentage of decentralized aircraft. A decrease in flexibility was found as the look-ahead time was increased up to 30 minutes, at which point the flexibility was fairly constant from a look-ahead time of 30 to 300 min. This is most likely due to a look-ahead time spanning most or all of many aircraft's flight plans which have around or less than 30 minutes in this airspace. Locus of control seemed to have no effect on the flexibility of the airspace (as implemented here).

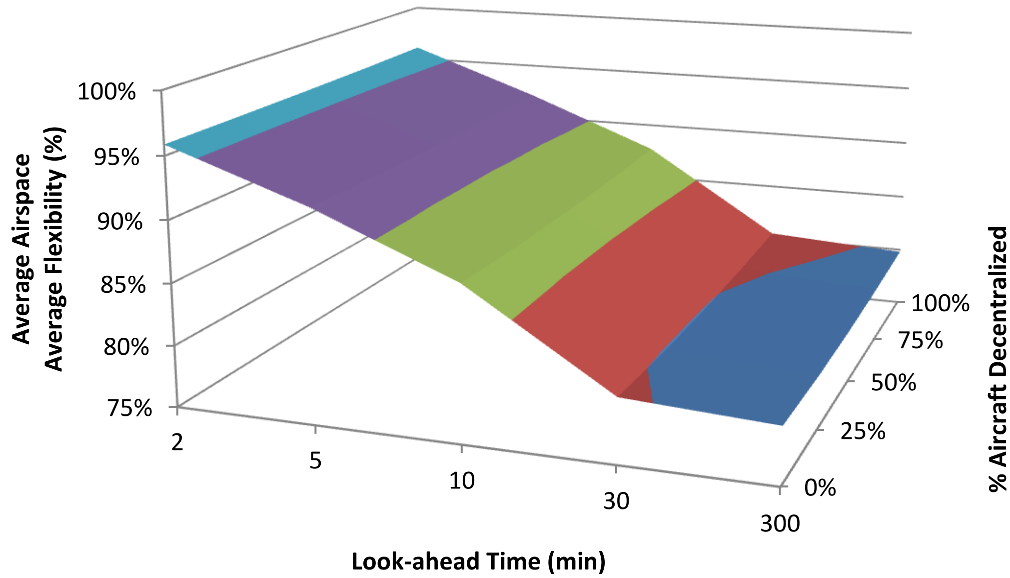


Figure 9 Airspace time-averaged average flexibility as a function of locus of control and look-head time, averaged across all traffic scenarios

4.1.2 Airspace Cost

Looking at the cost components (fuel and delay) over the airspace for each run (Figure 10), it appears that the more centralized the locus of control, the lower (better) the overall airspace cost. Also, the more decentralized the locus of control, the more the airspace cost varied. An interesting phenomenon to note is that most of the maneuvering aircraft seem to have ended up with flight plans that used less fuel than their original, (great circle) point-to-point flight plans.

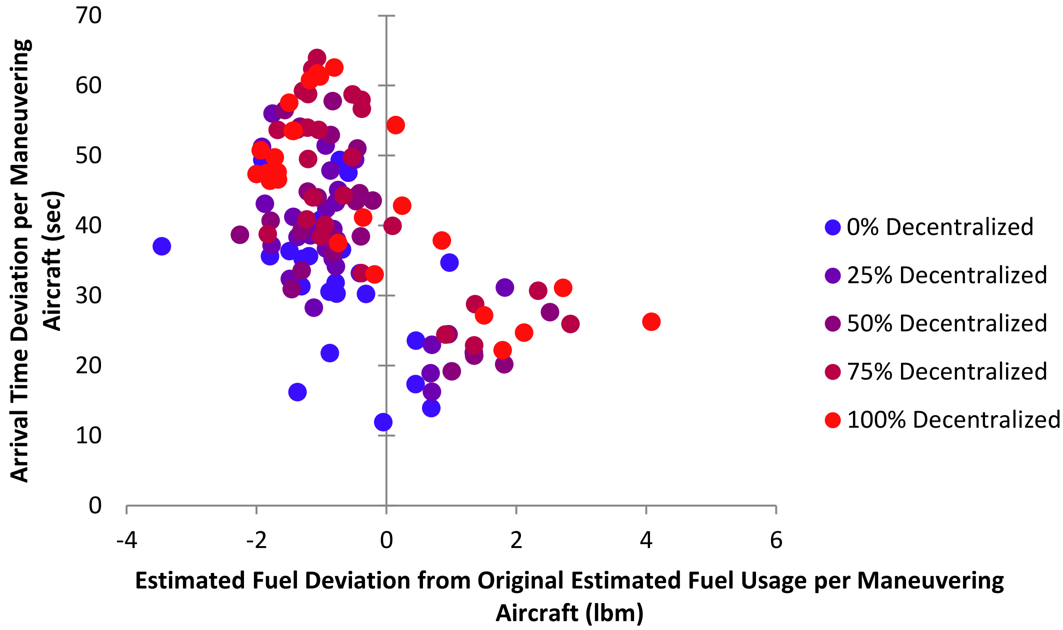


Figure 10 Cost components (fuel and delay) per run, color-coded by locus of control

The centralized implementation of CD&R (set in the 'hub experiment' to 'full average' cost mode) attempted to minimize the overall cost of maneuvers using the average cost index of all the aircraft in the airspace (past and future included) whereas the decentralized implementation (set to 'mixed' cost mode) attempted to minimize the cost assumed by each maneuvering aircraft using that aircraft's cost index. Thus, aircraft with more extreme cost indices (closer to 0% or 100% weighting on fuel versus delay) enjoy a lower cost per maneuver with the decentralized CD&R, and, conversely, the overall airspace cost is best minimized by a more centralized CD&R because it reflects on average the cost index of all the aircraft. As a side note, the full average airspace cost index ends up being about 50% in these runs because of the uniform distribution (from 0-100%) of the initial randomly generated (beforehand) number that determines each aircraft's cost index.

The estimated cost per maneuvering aircraft as a function of both look-ahead time and locus of control is shown in Figure 11. The decentralized CD&R implementation benefitted greatly from and even outperformed the centralized CD&R implementation (which actually performed slightly worse) with an increased look-head time. The decentralized CD&R implementation could only move the non-priority aircraft if a conflict resolution was found, which is not necessarily a cost-optimal solution. The centralized CD&R implementation was free to move either aircraft (if they were both under centralized control), so it could move the one that resulted in the lowest cost.

A longer look-ahead time benefitted the decentralized CD&R implementation most likely because it could resolve more aircraft conflicts (one by one) in a more strategic manner rather than in a more tactical-like manner (see section 4.1.5). The centralized CD&R implementation did not benefit from a longer look-ahead time, however. This is most likely because the solutions that produced the lowest cost for the smaller look-ahead times were not available with the longer look-ahead times because the longer look-ahead time corresponded to more conflicts that could not be resolved and, thus, caused all their 'branches' in the solution tree to be discarded.

The total airspace costs were re-calculated using the cost indices of each aircraft and the results can be seen in Figure 12. The centralized-controlled aircraft flight plan costs are the only affected values in this case because the centralized controller used a full average of all the aircraft cost indices to assess flight plan cost (see section 3.3.5). Despite this difference in flight plan cost calculation, the airspace cost values remain very similar to Figure 11. Only a slight increase in cost can be seen in the completely centralized (0% decentralized) runs, particularly at the 2 and 5 minute look-ahead times. This result suggests that given a uniform distribution of aircraft cost indices, simply using the average of the cost indices will produce very good overall results, despite some aircraft having very extreme (closer to 0% or 100%) cost indices.

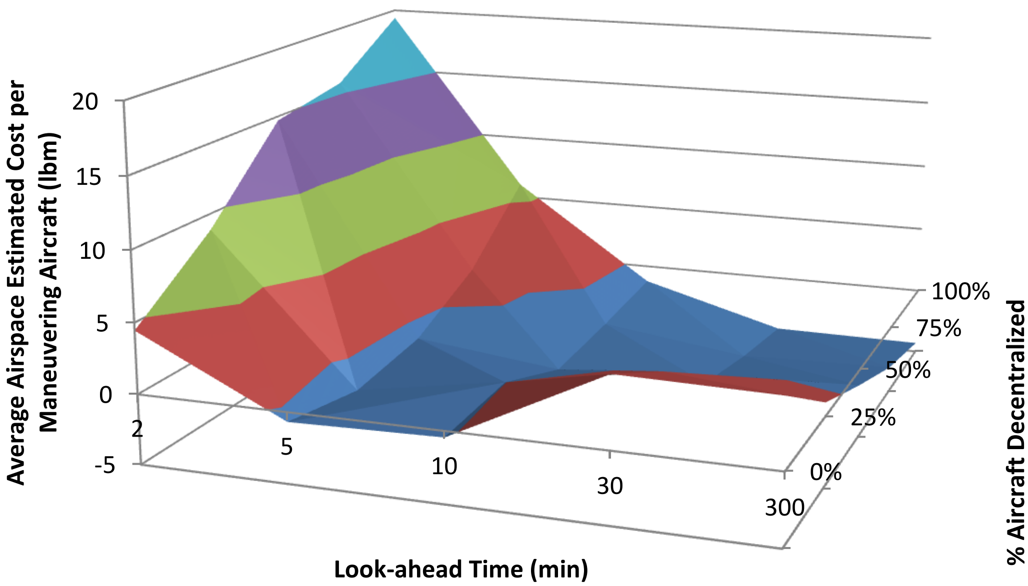


Figure 11 Average estimated cost per maneuvering aircraft as a function of locus of control and look-ahead time, calculated using the same cost indices as used for flight plan cost assessment within the CD&R calculations (decentralized used each individual aircraft's cost index while centralized used an average of the cost indices of all aircraft in the airspace)

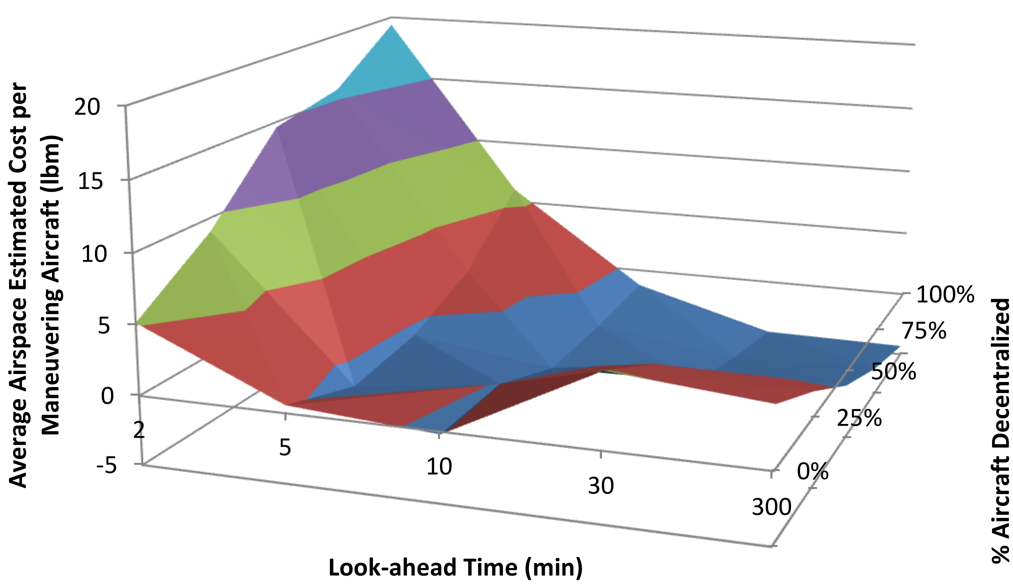


Figure 12 Average estimated cost per maneuvering aircraft as a function of locus of control and look-ahead time, calculated using each individual aircraft's cost index. Note that only the centralized aircraft flight plans result in a different cost value than shown in Figure 11

4.1.3 Number of Conflicts and Maneuvers per Aircraft

The look-ahead time generally had no effect on the number of conflicts or number of maneuvers made to resolve predicted conflicts; both were normalized by the number of aircraft (see Figure 13 and Figure 14). This is most likely because of the granular conflict resolution system described in section 3.5.6, that limits an aircraft's effective look-ahead time to that of its first conflict. While the locus of control had little effect on the number of conflicts per aircraft, it did have an effect on the number of maneuvers per aircraft, which may contribute to the results discussed next in section 4.1.4.

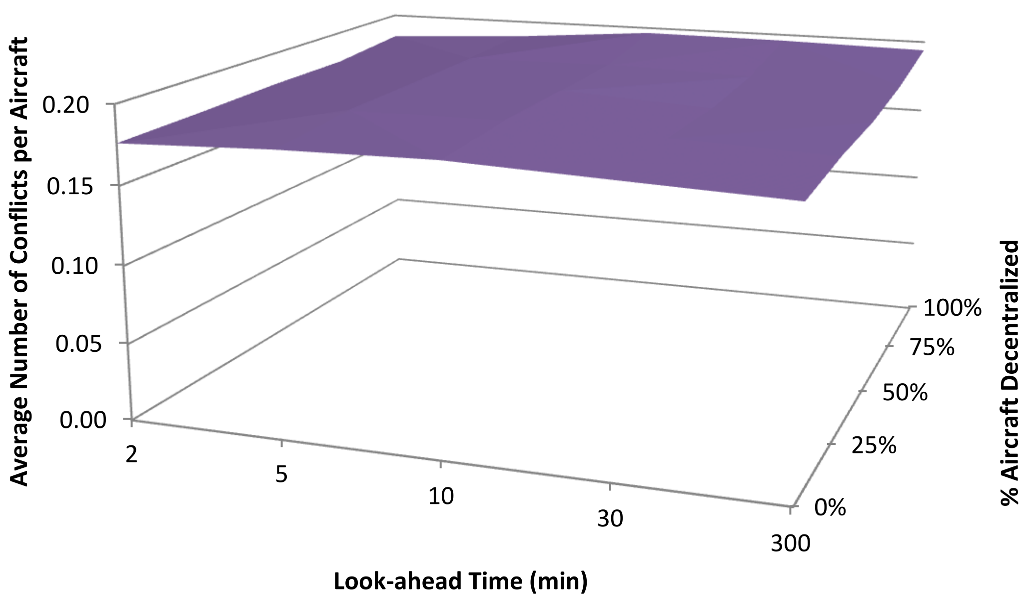


Figure 13 Average number of conflicts per aircraft as a function of locus of control and look-ahead time

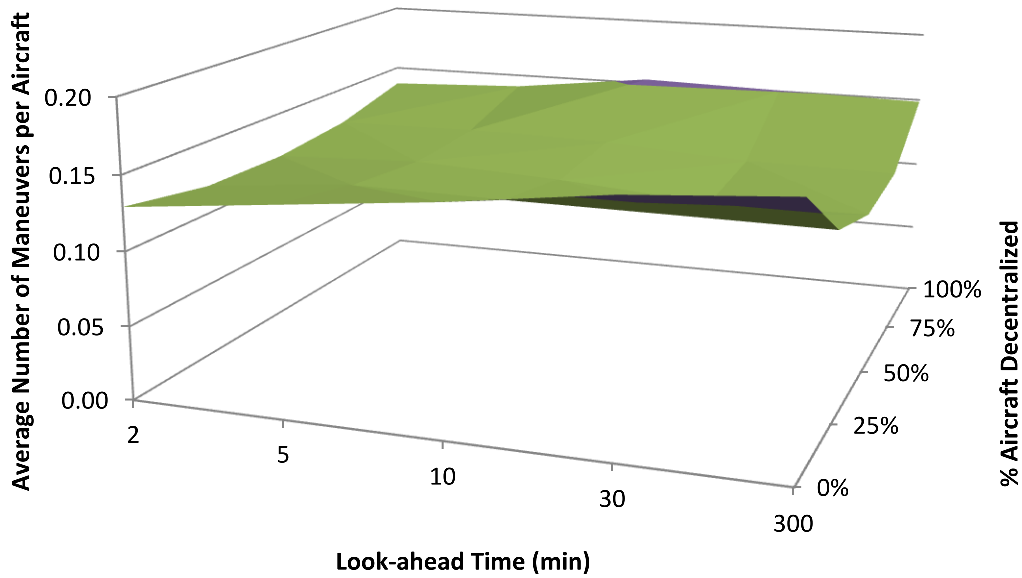


Figure 14 Average number of maneuvers per aircraft as a function of locus of control and look-ahead time

4.1.4 Unresolved Conflicts Leading to Losses of Separation

Not every conflict was resolved by the CD&R algorithm. Figure 15 shows the percentage of conflicts that were unresolved and resulted in a loss of separation as a function of locus of control and look-ahead time. Of particular note is the peak clearly seen at the cases with a 300 minute (essentially infinite) look-ahead time where both fully centralized and fully decentralized have lower values than loci of control with a mix of centralized- and decentralized-controlled aircraft. Recall that the centralized CD&R implementation tries to resolve a conflict by maneuvering both aircraft (but one at a time) if they're both under centralized control; the decentralized CD&R implementation, if both aircraft are under decentralized control, schedules the priority aircraft to attempt to resolve a conflict (a little later) whenever the non-priority aircraft is unable to resolve it. Recall also that if two aircraft involved in a conflict are under different loci of control (one centralized, one decentralized), the right-of-way policy dictates which aircraft must attempt to resolve the conflict. In these runs, it is the decentralized-controlled aircraft that is required to resolve the conflict as the centralized-controlled aircraft have the right-of-way.

The right-of-way policy has no provision for the right-of-way aircraft (centralized-controlled in these runs) to attempt to resolve the conflict if the non-right-of-way aircraft (decentralized-controlled in these runs) is unable to resolve the conflict. This lack of provision is most likely the cause of an increase in unresolved conflicts between mixed centralized- and decentralized- controlled aircraft, and subsequently, losses of separation. This is evident from the fact that the total number of conflicts remained flat throughout locus of control shifting (Figure 13) and the number of maneuvers had a slight inverted arch throughout locus of control shifting (Figure 14), indicating either conflict resolutions became more efficient with a mixed centralized-decentralized locus of control (in the sense of more conflicts resolved per maneuver) or (the more likely case) an increase in unresolved conflicts.

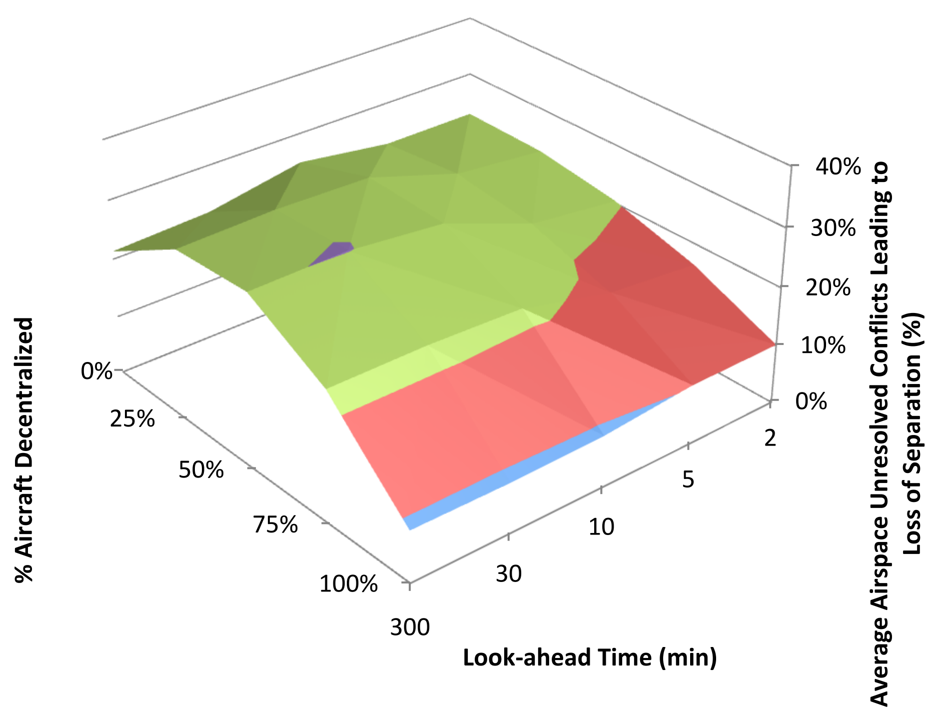


Figure 15 Average unresolved conflicts leading to losses of separation as a function of locus of control and look-ahead time

The centralized CD&R implementation most likely resolved fewer conflicts than the 100% decentralized CD&R because it was designed to stop working on a solution if a conflict could not be resolved (see section 3.5.6.1 for details). This effect has a slight increase as the look-ahead time increases because the centralized solution search tree deepens with an increased look-ahead time, increasing the possibility of an unresolvable conflict.

4.1.5 Detailed Analysis of Look-ahead Time Effects

To better understand why the cost resulting from decentralized CD&R is so high for a small look-ahead time especially as the number of maneuvers per aircraft slightly increased with increased look-ahead time, a detailed analysis was performed on specific, representative conflicts. This analysis was also performed to demonstrate the model detail provided by the simulation platform. Consider aircraft ‘AC0830’ in scenario 5, which conflicts with aircraft ‘AC0887’. With a 2 minute look-ahead time in a fully decentralized locus of control, it is apparent that this aircraft, in an attempt to resolve the first conflict with aircraft AC0887, creates 5 subsequent conflicts with the same aircraft due to the initial conflict resolution maneuver placing aircraft AC0830 on the left of aircraft AC0887 such that it then needs to find a maneuver back to its airspace exit point on its right (see Figures 16-23). These additional conflicts and maneuvers cause its final flight plan cost to end up at 340.06 lbm and can be likened to a ‘domino effect’ where resolutions of one conflict can cause another, as observed in prior research [17]. Note that the thicker the flight plan in each figure, the more maneuvers an aircraft has made.

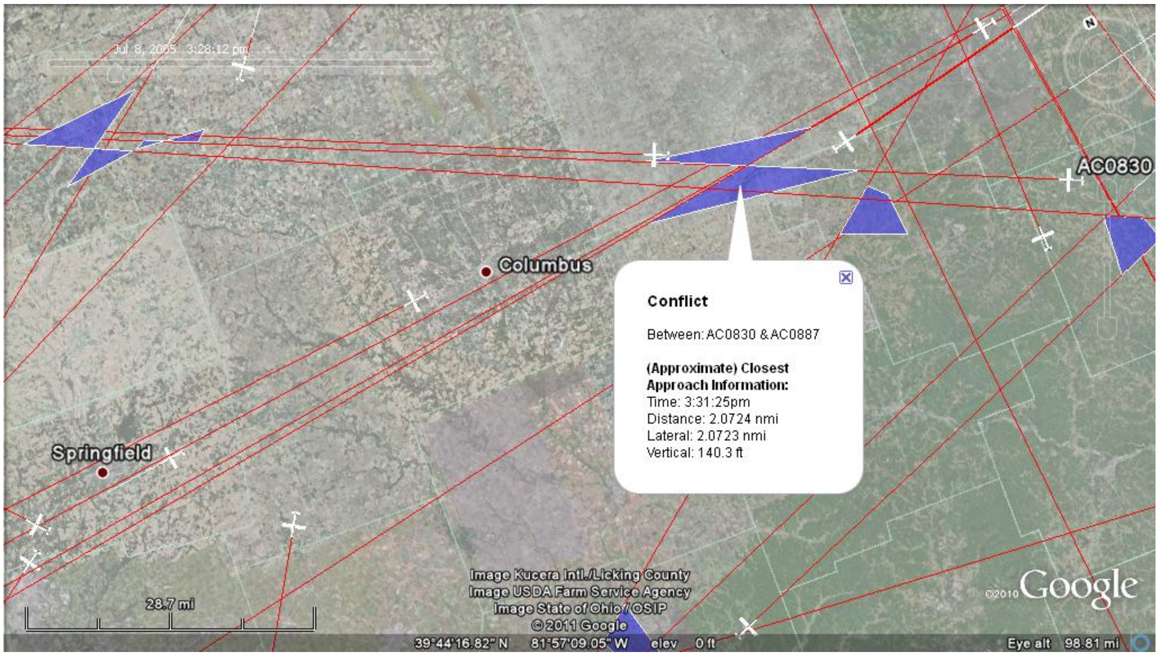


Figure 16 First conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time). No resolution has been attempted yet. The blue polygons represent conflicts and are drawn from the start time to the end time of the conflict on the flight plans for both aircraft involved in that conflict (for a total of 4 points).

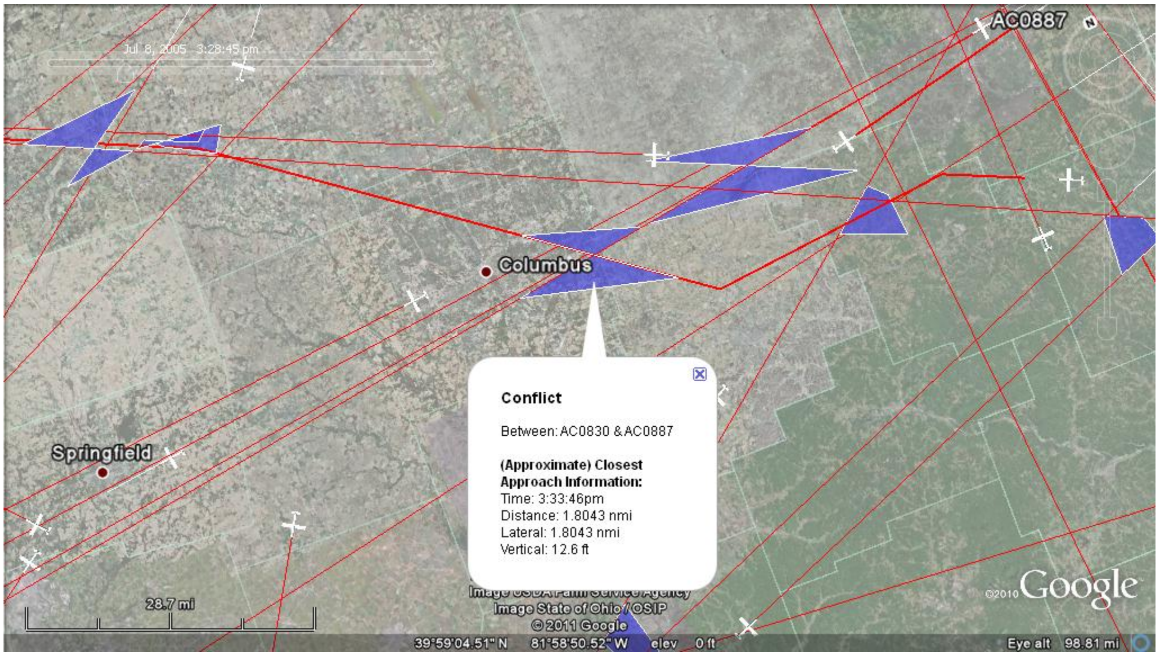


Figure 17 Second conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time). Note that the thicker the flight path, the more maneuvers the aircraft has made.

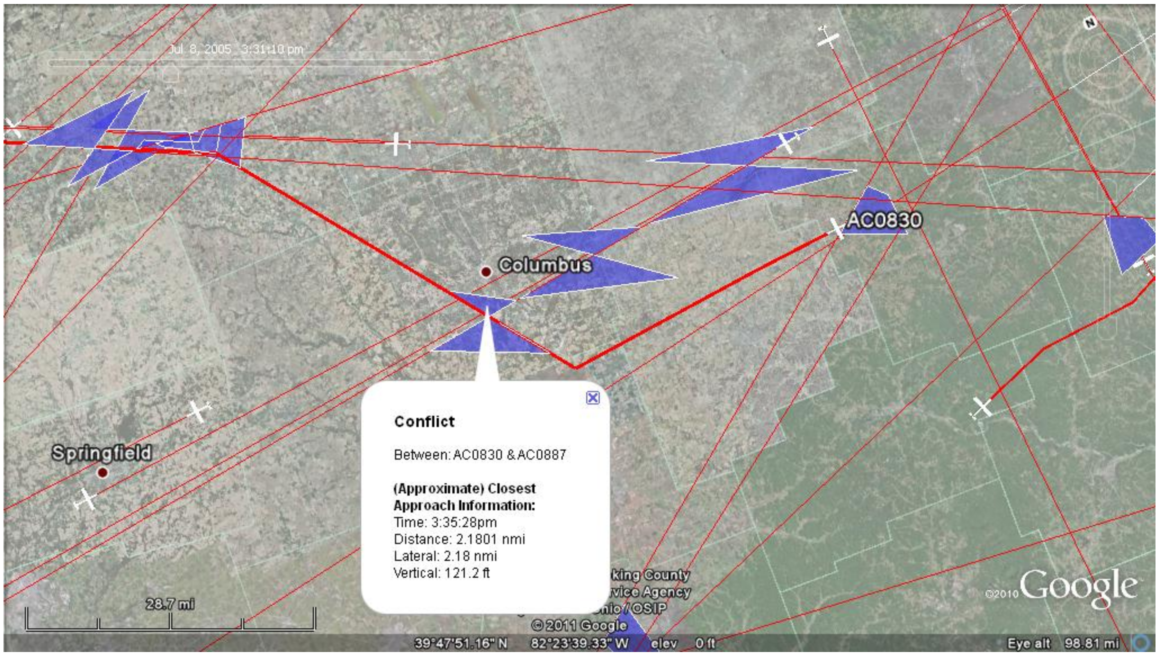


Figure 18 Third conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time)

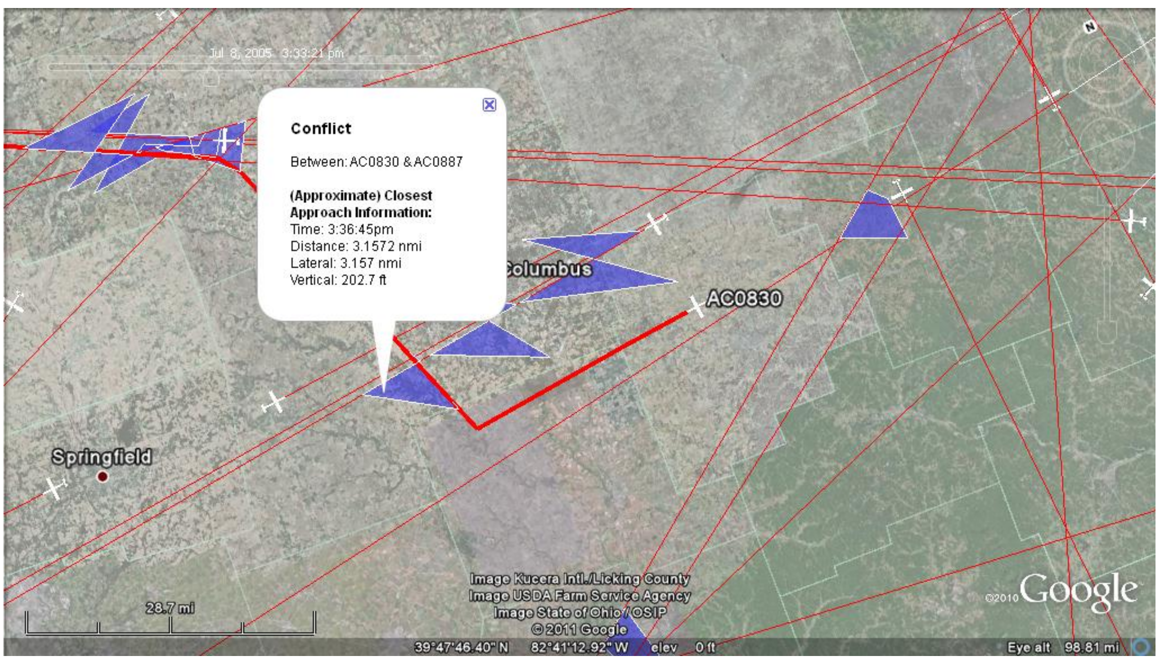


Figure 19 Fourth conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time). Between this figure and the previous, the vertical separation has increased because aircraft AC0887 is descending.

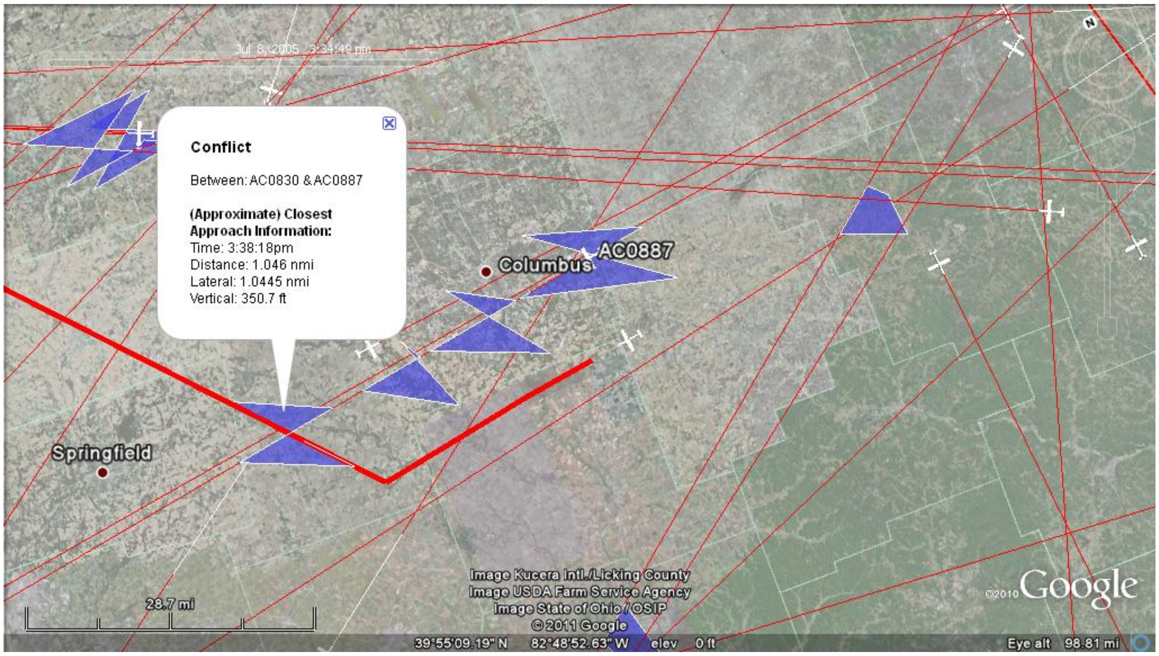


Figure 20 Fifth conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time)

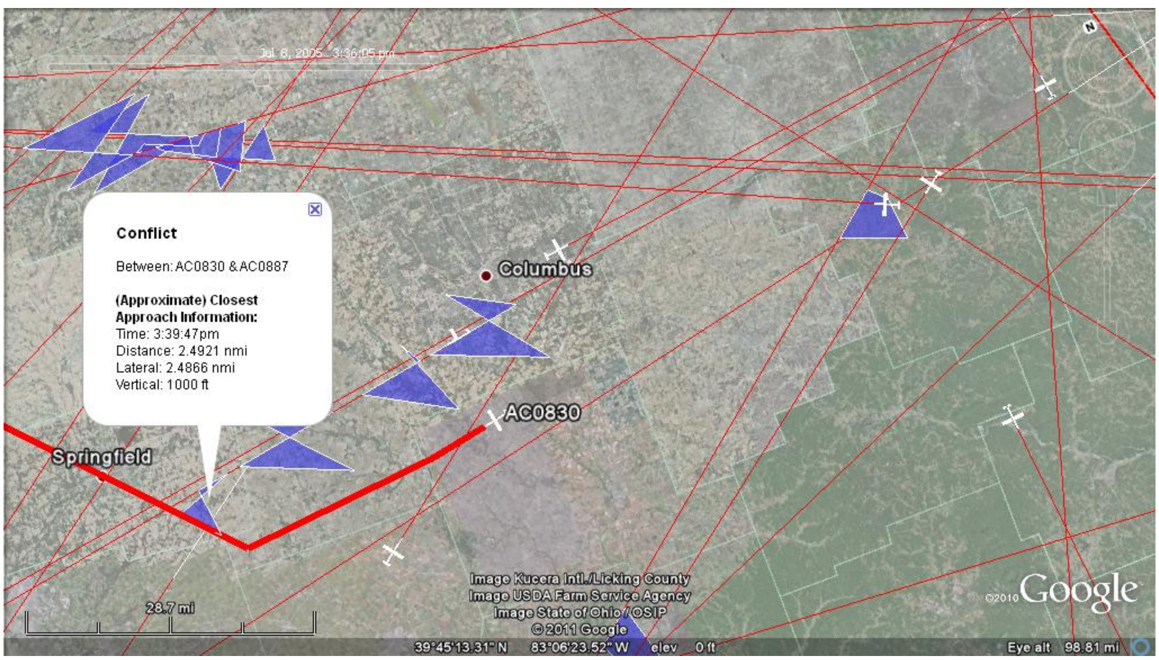


Figure 21 Sixth conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time). Note that the vertical separation is almost large enough to allow aircraft AC0830 to cross aircraft AC0887's flight path.

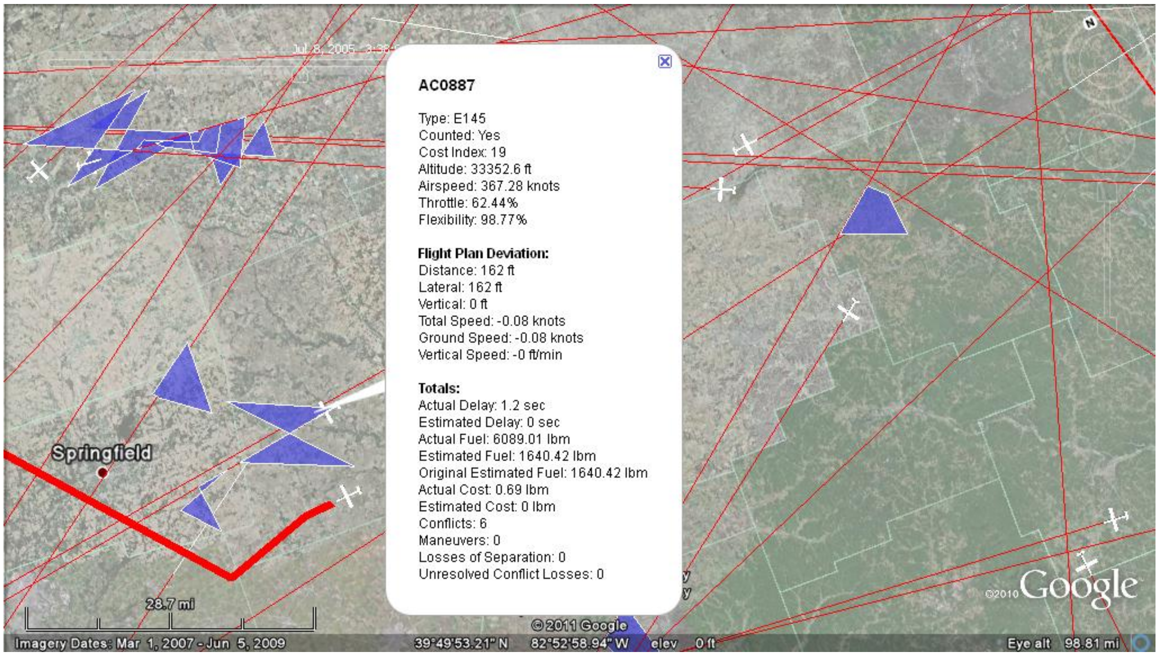


Figure 22 Conflict resolution between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time)

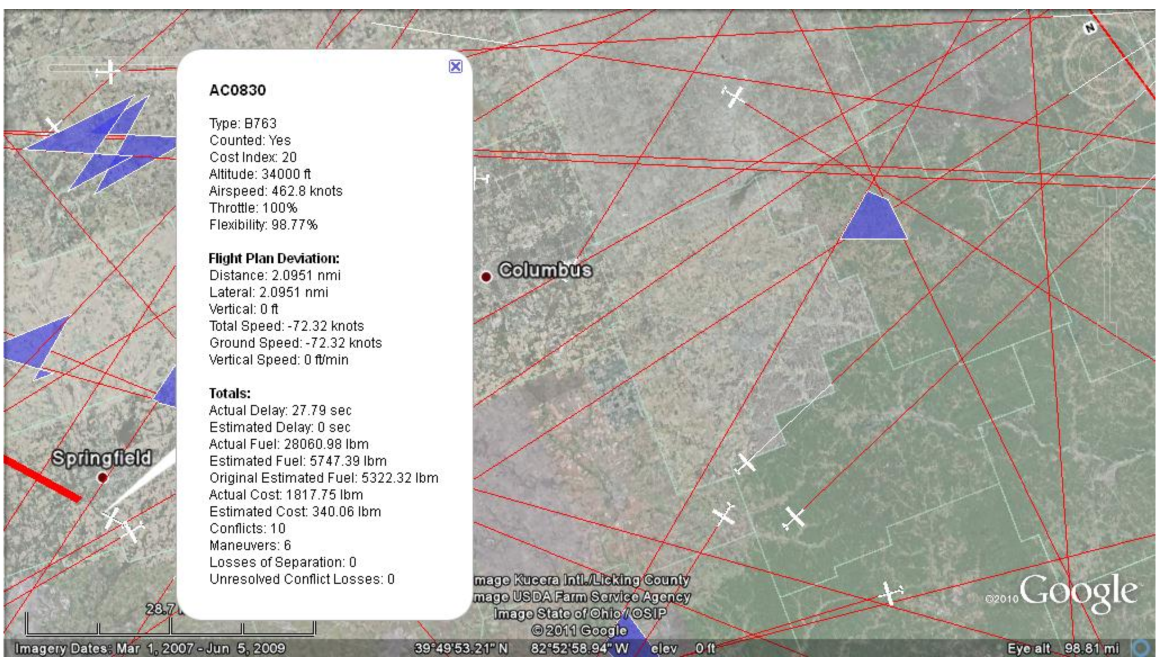


Figure 23 After the conflict between aircraft AC0830 and aircraft AC0887 (fully decentralized, 2 minute look-ahead time)

With a longer look-ahead time (5 minutes), the same aircraft in the same scenario still experienced one (but only one) additional conflict and ends up with a much lower-cost flight plan (82.41 lbm) (see Figure 24). A look-ahead time of 30 minutes produces a yet-lower cost flight plan at 47.68 lbm (Figure 25) but still with the additional conflict to subsequently resolve.

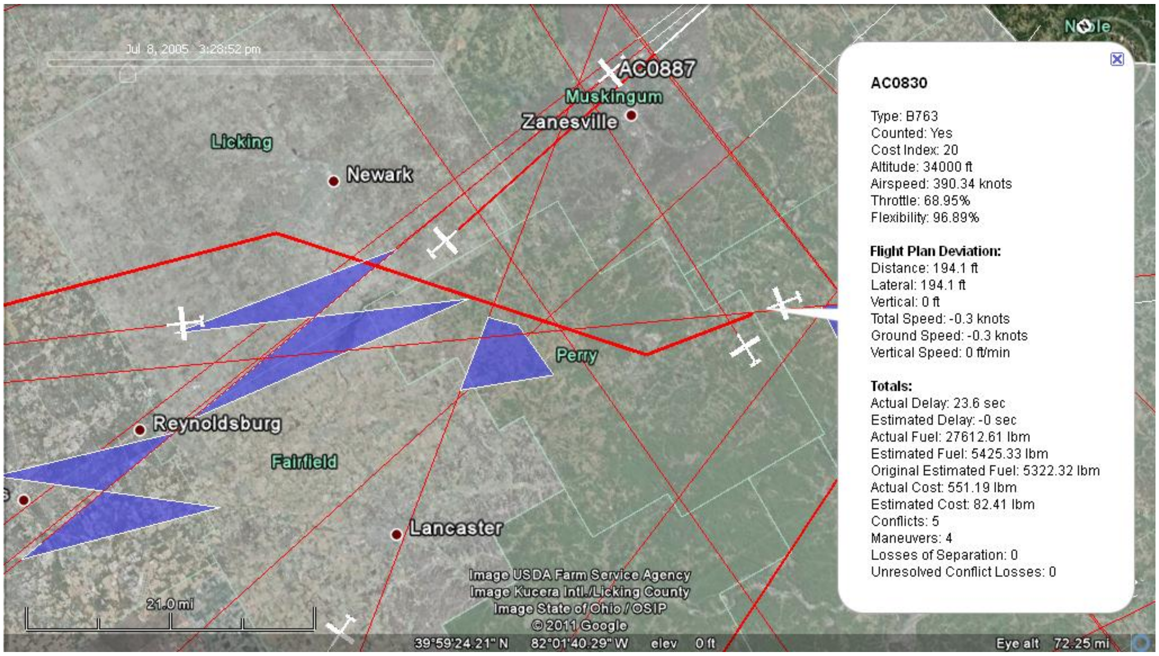


Figure 24 Conflict resolution between aircraft AC0830 and aircraft AC0887 (fully decentralized with a 5 minute look-ahead time)

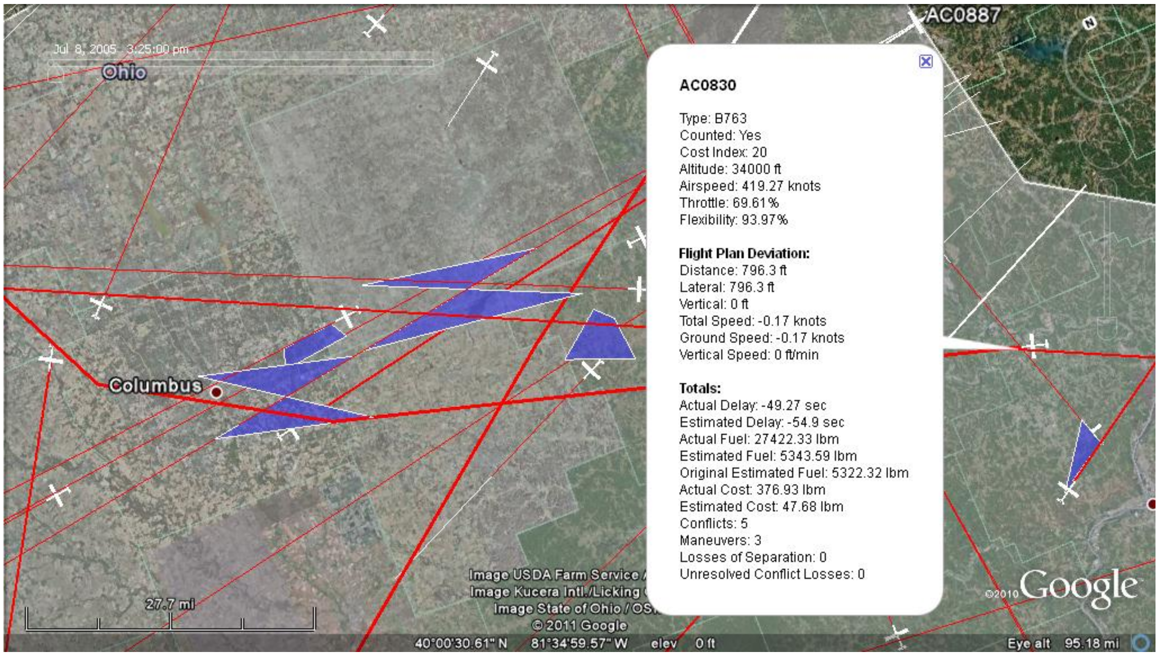


Figure 25 Conflict resolution between aircraft AC0830 and aircraft AC0887 (fully decentralized with a 30 minute look-ahead time)

The same scenario in a fully centralized airspace produces a vastly different solution: it simply moves the other aircraft, AC0887 (see Figure 26). This is because the centralized controller is able move either aircraft without being stymied by the priority rules driving the decentralized control in which aircraft AC0887 had right-of-way because it was descending (note the altitudes of aircraft AC0887) and, even if it weren't descending, because it was 'to the right' of aircraft AC0830 (see section 3.5.6.2 for a full description of the right-of-way rules).

It is of interest to note the sizes of the two aircraft. Aircraft AC0887 is a (relatively small) regional jet, while aircraft AC0830 is a large, wide-body passenger transport aircraft. This is most likely the reason it was a much lower cost for the centralized controller to move aircraft AC0887 instead of aircraft AC0830. It is also of interest to note that the centralized controller was able to find a flight path for aircraft AC0887 that used less fuel (by about an estimated 10 lbm) than the original point-to-point (great circle) flight plan.

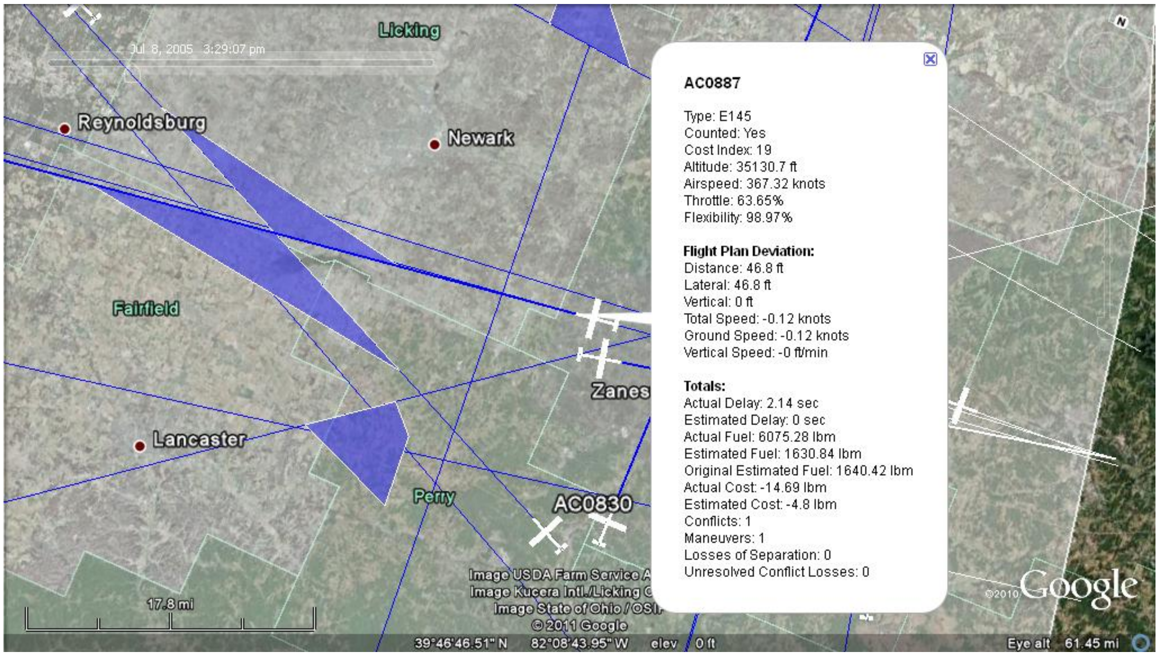


Figure 26 Conflict resolution between aircraft AC0830 and aircraft AC0887 (fully centralized conflict resolution with a 2 minute look-ahead time)

4.2 Scalability 'Spoke Experiment' Results

This spoke experiment examined how the effects noted in the 'hub experiment' scale with increasing traffic density. Thus, traffic densities of 1x, 2x, 3x, 4x, and 5x were run with all 5 scenarios to isolate any breakpoints where the metrics start to change significantly. The factors examined in the 'hub experiment' were fixed at a 100% decentralized locus of control and a 10 minute look-ahead time (because the centralized and decentralized CD&R implementations seemed to perform about the same at that value – see Figure 11). Although the absolute number of conflicts per aircraft increases with increasing traffic density (see Figure 27), the percentage of unresolved conflicts resulting in losses of separation initially decreases. The breakpoint is defined as the traffic density where the percentage of conflicts that are unresolved (and result in losses of separation) versus traffic density then develops a positive slope with increasing traffic density. The breakpoint was found to vary by scenario but in general to be around 3 to 4x traffic density (see Figure 28). In addition, the flexibility was measured as a function of traffic density, and found to decrease with an increase in traffic density (see Figure 29).

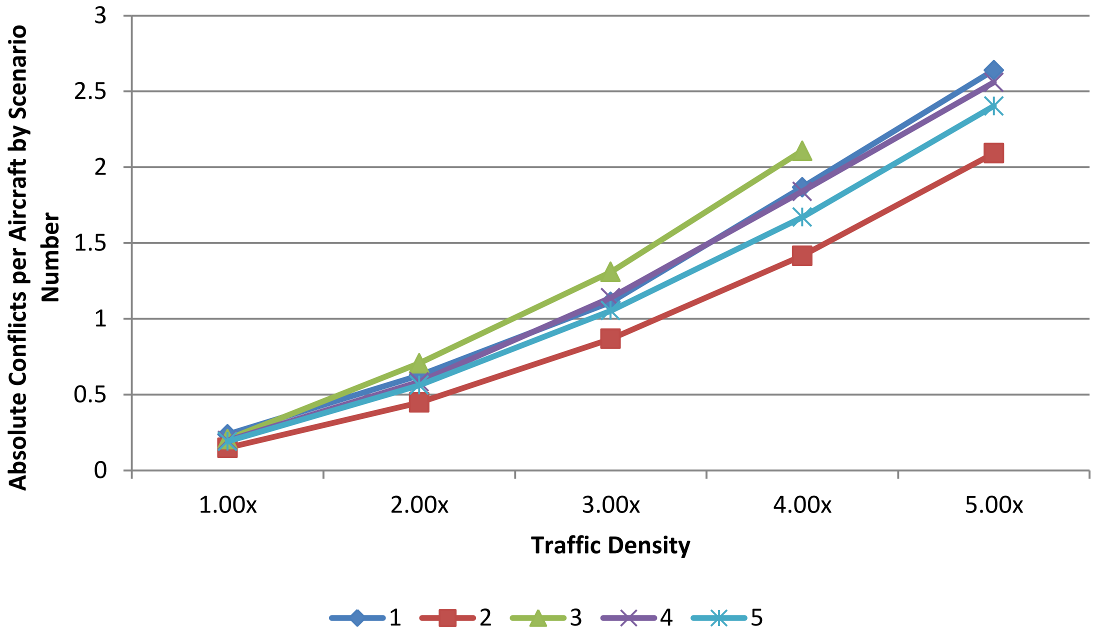
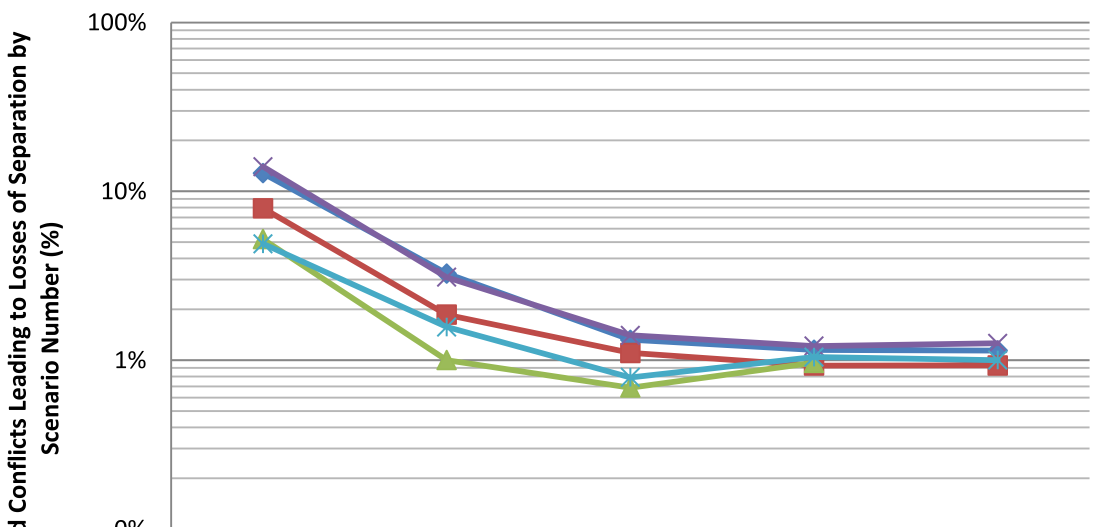


Figure 27 Conflicts per aircraft by scenario as a function of traffic density for 100% decentralized locus of control and a 10 minute look-ahead time



	1.00x	2.00x	3.00x	4.00x	5.00x
1	12.787%	3.259%	1.321%	1.152%	1.142%
2	7.937%	1.862%	1.105%	0.930%	0.932%
3	5.212%	1.003%	0.688%	0.965%	
4	13.986%	3.098%	1.404%	1.214%	1.259%
5	4.887%	1.573%	0.791%	1.044%	1.003%

Traffic Density

Figure 28 Percentage of conflicts that are unresolved and lead to losses of separation by scenario number as a function of traffic density for 100% decentralized locus of control and a 10 minute look-ahead time

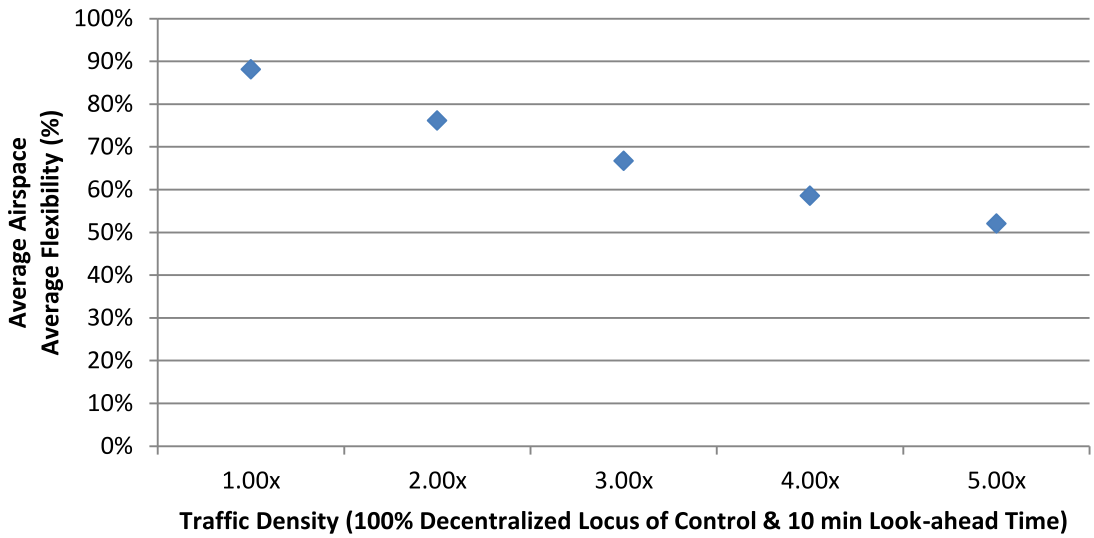


Figure 29 Average airspace average flexibility versus traffic density for 100% decentralized locus of control and a 10 minute look-ahead time. Note that the data point at 5x does not contain data from scenario 3.

Another interesting result is the number of aircraft in each scenario versus the order of appearance of each scenario data set in Figure 27 and Figure 28. Although each scenario had roughly the same number of aircraft, scenario 2 had the least number (1613 at 1x traffic density) and scenario 3 had the most (1859 at 1x traffic density). Scenario 2 has the least conflicts and scenario 3 has the most, visible in Figure 27. However, the percentage of unresolved conflicts that resulted in losses shown in Figure 28 does not show any consistent difference between scenarios ordered by the exact number of aircraft in each. This suggests that aircraft number (or traffic density) is not the only driving factor with these airspace metrics: some aspect of the 'complexity' of each traffic scenario is also affecting the results.

4.3 Simulation Runtime

Because of the fast-time simulation capability of WMC, the runtime of the simulation was often much less than the real time span modeled in the scenarios. Speedup factors of almost 10x were common on a single core of a 2.8 GHz processor for scenarios spanning 5 hours and an average of 1733 aircraft. However, longer look-ahead times required the CD&R implementation to resolve more conflicts for both centralized and decentralized loci of control (see Figure 31). Likewise, the decentralized CD&R implementation ran slower with very short look-ahead times, likely due to poor conflict resolution options resulting from short look-ahead times and priority rules then requiring further maneuvers to resolve subsequent conflicts. However, the centralized CD&R implementation consumed a good amount (and sometimes most) of the computational time, especially with longer look-ahead times (and when tested with higher traffic densities). This is because of the computational overhead of parsing the search tree used here.

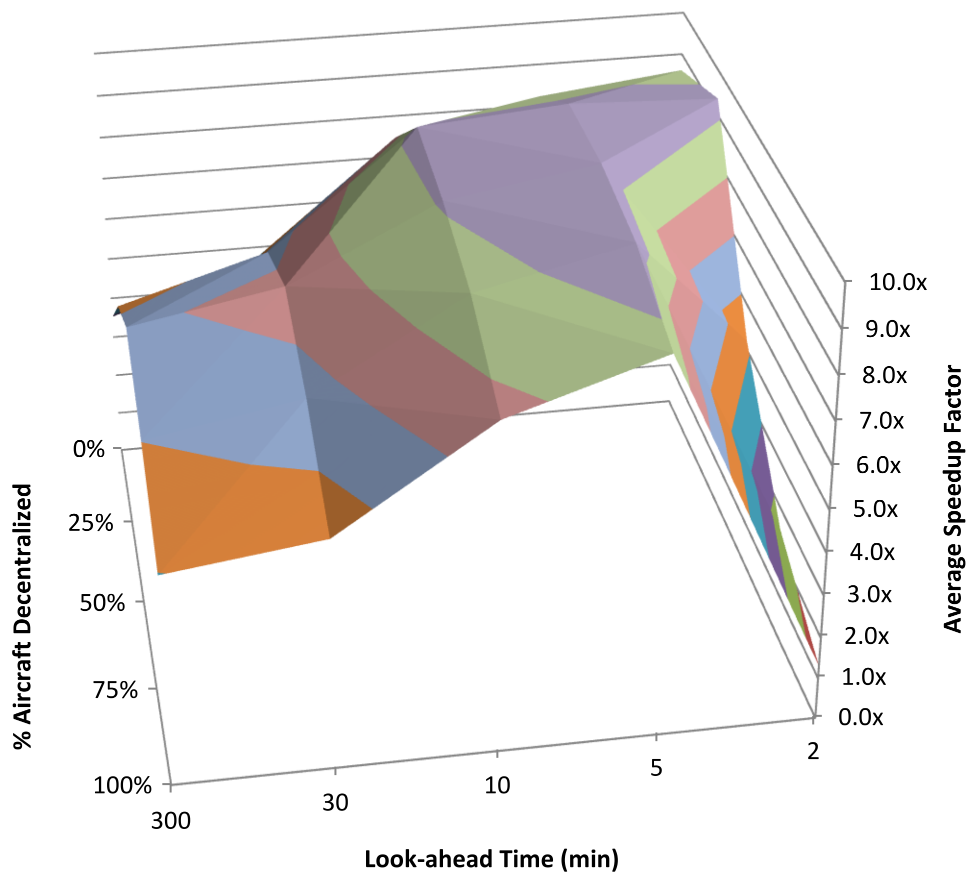


Figure 30 Simulation speedup relative to real-time

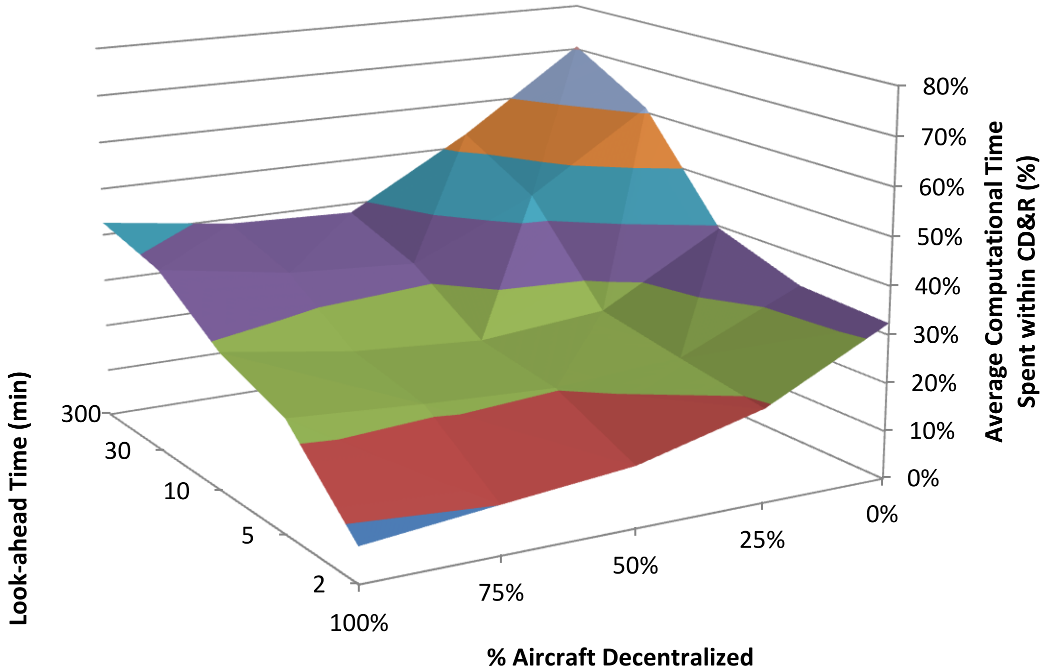


Figure 31 Percentage of processor time used by the conflict detection and resolution implementation

CHAPTER 5

CONCLUSIONS

5.1 Summary

A general framework was developed to properly assess relative costs and benefits of innovative air traffic concepts of operations. At its top level, this framework provides both definitions of essential airspace aspects, and metrics of the relative costs and benefits of airspace concepts of operation as defined by these aspects. Three essential airspace aspects were identified: safety, which can be achieved through separation assurance; transport, which is established by trajectory determination; and fairness assurance, which is established by policies dictating, for example, right-of-way. The metrics outlined by the framework include flexibility of an aircraft (i.e., its allowable trajectory change without causing a conflict) and of the airspace (an aggregation of aircraft flexibility), the robustness (a comparison of metrics observed in nominal versus off-nominal conditions), as well as several common aircraft performance metrics such as delay and fuel burn that can be aggregated to indicate the performance of the airspace as a whole.

The second level of the framework deals with testing a novel airspace concept of operation. Such testing requires evaluation methods appropriate to the concept(s) of operation to be analyzed. In this thesis, the locus of control was varied between concepts of operation. Therefore, the evaluation method applied a common CD&R algorithm to make direct comparisons of the concepts of operation applying different loci of control without confounds due to different CD&R algorithms. This was accomplished by providing two implementations of the same CD&R algorithm, one centralized and the other decentralized, that each attempt to mimic real-world implementations.

The final level of the framework applies simulation to analyze specific concepts of interest. This thesis used the WMC simulation platform, with the addition of several simulation tools established to model airspace, aircraft and CD&R. Aircraft dynamic models utilized BADA performance data. The airspace itself had several actions that enabled creating and removing aircraft, performing CD&R, and checking for losses of separation. A traffic multiplier tool created the capability for repeatable re-creation of traffic scenarios of varying traffic density, acting upon an initial traffic configuration established from ETMS data to represent four hours of operation of the Indianapolis Center. A database was used to both store the initial aircraft data and flight plans as well as the output metrics.

In the 'hub experiment' the simulation was configured to examine the effects of a range of loci of control as well as CD&R look-ahead time on the aggregate airspace metrics described in the top level of the framework. To illustrate the types of aggregate measures captured, the flexibility of the airspace was found to be fairly constant with respect to locus of control, but decreased with increased look-ahead time until 30 minutes of look-ahead time was reached, at which point the flexibility did not further change significantly. Similarly, the centralized CD&R implementation was better at minimizing both fuel and delay costs simultaneously, providing more of an airspace-wide optimal traffic management solution, while, at longer look-ahead times, the decentralized CD&R implementation was more adept at minimizing them with respect to each aircraft, providing a more user-specific optimal traffic management solution. Locus of control had an additional unexpected effect: in a concept of operations allowing for a mix of centralized- and decentralized-controlled aircraft, the percentage of conflicts that went unresolved (and therefore caused loss of separation) increased; more detailed examination found gaps in the CD&R logic for assigning conflict resolution maneuvers to aircraft operating under different control schemes as driven by priority and right-of-way policies.

As further illustration of insights provided by the simulation platform, the number of conflicts and maneuvers was found to be fairly constant with respect to look-ahead time, perhaps because the CD&R algorithm evaluated only the first conflict experienced by each aircraft regardless of look-ahead time. When comparing airspace cost, the decentralized CD&R implementation seemed to benefit greatly from an increased look-ahead time while the centralized CD&R implementation performance was slightly reduced with an increased look-ahead time. A ‘domino effect’ was observed on a per-aircraft basis and contributed to significant increases in airspace cost at smaller look-ahead times for the decentralized CD&R implementation. Results suggest this effect and therefore increase in cost may be mitigated by examining other rules within this CD&R implementation to better assess cost. Finally, with increasing look-ahead time the centralized CD&R implementation used here was found to consume a significant portion of the computation time, supporting the notion that a decentralized and distributed control paradigm may be a more feasible traffic management option.

The mechanisms for conducting additional 'spoke experiments', including robustness testing, were described. To demonstrate, the ‘scalability spoke experiment' was conducted. The flexibility of the airspace was found to also decrease with increased traffic density. Somewhere between about 3 and 4x traffic density, the percentage of conflicts that are not resolved by the CD&R algorithm and result in loss of separation begins to increase substantially, suggesting this traffic density range reflects an inflection point in the relationships between traffic density and metrics of airspace operations.

The detail of the simulation models allowed the specific causes underlying these effects to be examined in more detail. For example, in a more detailed examination of the decentralized CD&R implementation, the trend with look-ahead time identified in the hub experiment was found to result from aircraft priority rules that caused emergent behaviors in the interaction between aircraft of varying priority and the CD&R algorithm’s response to their maneuvers. Similarly, the CD&R implementation sought to assign the resolution to ‘appropriate’ aircraft (based on either the aircraft whose resolution would have the lowest cost or the aircraft with lowest priority). However, the aircraft’s effective look-ahead time was restricted to the end time of the most immediate conflict, and subsequent conflicts could then arise after the immediate conflict was resolved.

5.2 Contributions

The contribution of this work is twofold. First, a framework was constructed to explore the costs and benefits of various air traffic concepts of operation. The framework will not only enable the community, including air navigation service providers, to effectively compare different concepts of operation and locus of control considerations for efficient trajectory determination and traffic management, but also enable future users of the airspace to tailor the costs and benefits of the different control paradigms to their individual needs.

Second, novel air traffic management concepts varying the locus of control were explored. The ‘hub’ and scalability ‘spoke’ experiments illustrated both the aggregate metrics, and the ability of the simulation platform to provide detailed analysis of the behavior within the concepts of operation contributing to overall metrics.

5.3 Future Work

The remaining ‘spoke experiments’ (detection range, robustness, right-of-way rules and policies, costs, communication limits, and airspace access rules) described in section 3.3 are all excellent candidates for future work relating to this thesis. Additionally, there are many other potential extensions:

- The inclusion of partial conflict resolutions in the centralized CD&R implementation could reduce the number of unresolved conflicts at higher look-ahead times for the centralized-controlled aircraft. However, a decision must be made when a lower cost partial resolution and a higher-cost complete resolution are available as to which one should be used.

- The decentralized CD&R implementation could be improved by somehow including costs alongside the priority rules to limit the effects at shorter look-ahead times described in section 4.1.5.
- The StratWay CD&R algorithm could possibly be used more effectively by using a less granular conflict resolution method.
- Gaming analysis could seek to understand possible strategies by individual aircraft or airlines to exploit novel airspace concepts of operation, particularly examining policies implemented to address fairness assurance.
- While this thesis focused on aircraft being under one locus of control or another for their entire flight, dynamic locus of control, or the ability for an aircraft to change its locus of control during flight, is a possibility and could be explored in great detail.
- Gaming analysis of dynamic loci of control becomes very important as aircraft (or airlines) may switch loci of control temporarily in order to dodge certain policies at certain times.
- The robustness of the various control paradigms to failures in communication, navigation, and/or surveillance functions could be tested and is an important and relevant topic as dependence on complex equipment increases.
- Economic and technological feasibility of novel air traffic management concepts is a driving factor in adoption of these new concepts and needs to be understood as well.

Further development of the airspace concepts of operation discussed in this thesis are possible as well as the introduction of other airspace concepts. These concepts could include things such as mandating that certain airspace areas have a certain percentage of loci of control could be explored and may be necessary in terminal radar approach control

(TRACON) areas in order to reduce competition for departure and/or arrival slots. Finally, the incorporation of this framework into business models of the airspace users could be of great benefit not only to the users of the airspace, but potentially for new airspace concept and/or technology adoption.

APPENDIX A

RAW DATA

A.1 Aggregate Airspace Data

The aggregate airspace raw data for each run can be found in tables 2-6.

Table 2 Flexibility data and aircraft counts

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Flexibility (%)	Total Aircraft	Total Centralized Aircraft	Total Decentralized Aircraft	Total Counted Aircraft	Centralized Counted Aircraft	Decentralized Counted Aircraft	Counted Maneuvering Aircraft	Centralized Counted Maneuvering Aircraft	Decentralized Counted Maneuvering Aircraft
10000101	1	0%	1.00x	2	95.04%	1621	1621	0	1285	1285	0	118	118	0
10000102	2	0%	1.00x	2	96.74%	1613	1613	0	1270	1270	0	118	118	0
10000103	3	0%	1.00x	2	95.52%	1859	1859	0	1491	1491	0	178	178	0
10000104	4	0%	1.00x	2	95.68%	1822	1822	0	1445	1445	0	127	127	0
10000105	5	0%	1.00x	2	96.40%	1749	1749	0	1392	1392	0	144	144	0
10250101	1	25%	1.00x	2	95.04%	1621	1222	399	1283	962	321	118	75	43
10250102	2	25%	1.00x	2	96.72%	1613	1209	404	1270	956	314	109	76	33
10250103	3	25%	1.00x	2	95.60%	1859	1393	466	1491	1119	372	166	106	60
10250104	4	25%	1.00x	2	95.56%	1822	1368	454	1444	1093	351	118	79	39
10250105	5	25%	1.00x	2	96.47%	1749	1312	437	1393	1041	352	148	80	68
10500101	1	50%	1.00x	2	95.05%	1621	814	807	1284	658	626	123	34	89
10500102	2	50%	1.00x	2	96.73%	1613	800	813	1269	651	618	105	35	70
10500103	3	50%	1.00x	2	95.69%	1859	926	933	1489	743	746	165	50	115
10500104	4	50%	1.00x	2	95.61%	1822	906	916	1445	719	726	103	34	69
10500105	5	50%	1.00x	2	96.46%	1749	872	877	1393	688	705	147	42	105
10750101	1	75%	1.00x	2	95.13%	1621	408	1213	1284	335	949	128	4	124
10750102	2	75%	1.00x	2	96.78%	1613	402	1211	1268	330	938	107	9	98
10750103	3	75%	1.00x	2	95.79%	1859	455	1404	1488	369	1119	171	9	162
10750104	4	75%	1.00x	2	95.71%	1822	449	1373	1445	347	1098	122	10	112
10750105	5	75%	1.00x	2	96.45%	1749	434	1315	1392	338	1054	145	8	137
11000101	1	100%	1.00x	2	95.40%	1621	0	1621	1283	0	1283	138	0	138
11000102	2	100%	1.00x	2	96.83%	1613	0	1613	1268	0	1268	114	0	114
11000103	3	100%	1.00x	2	95.81%	1859	0	1859	1488	0	1488	181	0	181
11000104	4	100%	1.00x	2	95.90%	1822	0	1822	1444	0	1444	142	0	142
11000105	5	100%	1.00x	2	96.57%	1749	0	1749	1392	0	1392	159	0	159
20000101	1	0%	1.00x	5	90.94%	1621	1621	0	1284	1284	0	117	117	0
20000102	2	0%	1.00x	5	93.40%	1613	1613	0	1271	1271	0	112	112	0
20000103	3	0%	1.00x	5	91.52%	1859	1859	0	1491	1491	0	177	177	0
20000104	4	0%	1.00x	5	91.59%	1822	1822	0	1445	1445	0	129	129	0
20000105	5	0%	1.00x	5	92.69%	1749	1749	0	1393	1393	0	141	141	0
20250101	1	25%	1.00x	5	90.93%	1621	1222	399	1284	963	321	113	75	38

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Flexibility (%)	Total Aircraft	Total Centralized Aircraft	Total Decentralized Aircraft	Total Counted Aircraft	Centralized Counted Aircraft	Decentralized Counted Aircraft	Counted Maneuvering Aircraft	Centralized Counted Maneuvering Aircraft	Decentralized Counted Maneuvering Aircraft
20250102	2	25%	1.00x	5	93.22%	1613	1209	404	1271	957	314	104	74	30
20250103	3	25%	1.00x	5	91.42%	1859	1393	466	1490	1118	372	162	106	56
20250104	4	25%	1.00x	5	91.62%	1822	1368	454	1444	1093	351	122	80	42
20250105	5	25%	1.00x	5	92.70%	1749	1312	437	1393	1041	352	145	81	64
20500101	1	50%	1.00x	5	90.70%	1621	814	807	1284	658	626	117	34	83
20500102	2	50%	1.00x	5	93.23%	1613	800	813	1271	652	619	101	33	68
20500103	3	50%	1.00x	5	91.53%	1859	926	933	1491	743	748	164	48	116
20500104	4	50%	1.00x	5	91.55%	1822	906	916	1444	719	725	105	33	72
20500105	5	50%	1.00x	5	92.71%	1749	872	877	1393	688	705	144	38	106
20750101	1	75%	1.00x	5	90.87%	1621	408	1213	1284	335	949	125	4	121
20750102	2	75%	1.00x	5	93.19%	1613	402	1211	1271	331	940	105	9	96
20750103	3	75%	1.00x	5	91.56%	1859	455	1404	1490	369	1121	171	9	162
20750104	4	75%	1.00x	5	91.56%	1822	449	1373	1443	347	1096	113	10	103
20750105	5	75%	1.00x	5	92.73%	1749	434	1315	1392	338	1054	142	8	134
21000101	1	100%	1.00x	5	91.23%	1621	0	1621	1284	0	1284	139	0	139
21000102	2	100%	1.00x	5	93.22%	1613	0	1613	1271	0	1271	120	0	120
21000103	3	100%	1.00x	5	91.55%	1859	0	1859	1491	0	1491	186	0	186
21000104	4	100%	1.00x	5	91.82%	1822	0	1822	1443	0	1443	134	0	134
21000105	5	100%	1.00x	5	92.84%	1749	0	1749	1392	0	1392	157	0	157
30000101	1	0%	1.00x	10	86.02%	1621	1621	0	1283	1283	0	110	110	0
30000102	2	0%	1.00x	10	89.20%	1613	1613	0	1271	1271	0	108	108	0
30000103	3	0%	1.00x	10	86.74%	1859	1859	0	1490	1490	0	172	172	0
30000104	4	0%	1.00x	10	86.75%	1822	1822	0	1444	1444	0	119	119	0
30000105	5	0%	1.00x	10	88.22%	1749	1749	0	1393	1393	0	137	137	0
30250101	1	25%	1.00x	10	85.88%	1621	1222	399	1284	963	321	102	71	31
30250102	2	25%	1.00x	10	88.90%	1613	1209	404	1271	957	314	97	71	26
30250103	3	25%	1.00x	10	86.67%	1859	1393	466	1491	1119	372	154	105	49
30250104	4	25%	1.00x	10	86.66%	1822	1368	454	1444	1093	351	106	72	34
30250105	5	25%	1.00x	10	88.09%	1749	1312	437	1393	1041	352	127	72	55
30500101	1	50%	1.00x	10	85.74%	1621	814	807	1284	658	626	108	34	74
30500102	2	50%	1.00x	10	89.06%	1613	800	813	1271	652	619	89	30	59
30500103	3	50%	1.00x	10	86.79%	1859	926	933	1491	743	748	150	47	103
30500104	4	50%	1.00x	10	86.65%	1822	906	916	1444	719	725	99	31	68
30500105	5	50%	1.00x	10	88.11%	1749	872	877	1392	688	704	126	35	91
30750101	1	75%	1.00x	10	86.07%	1621	408	1213	1283	335	948	117	3	114
30750102	2	75%	1.00x	10	89.19%	1613	402	1211	1271	331	940	96	7	89
30750103	3	75%	1.00x	10	86.99%	1859	455	1404	1490	369	1121	163	9	154
30750104	4	75%	1.00x	10	86.75%	1822	449	1373	1444	347	1097	109	9	100
30750105	5	75%	1.00x	10	88.15%	1749	434	1315	1392	338	1054	127	7	120
31000101	1	100%	1.00x	10	86.64%	1621	0	1621	1283	0	1283	140	0	140
31000102	2	100%	1.00x	10	89.33%	1613	0	1613	1272	0	1272	123	0	123
31000103	3	100%	1.00x	10	87.12%	1859	0	1859	1490	0	1490	183	0	183
31000104	4	100%	1.00x	10	87.09%	1822	0	1822	1444	0	1444	138	0	138
31000105	5	100%	1.00x	10	88.41%	1749	0	1749	1393	0	1393	160	0	160
31000201	1	100%	2.00x	10	74.60%	3242	0	3242	2790	0	2790	669	0	669
31000202	2	100%	2.00x	10	77.96%	3226	0	3226	2760	0	2760	558	0	558

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Flexibility (%)	Total Aircraft	Total Centralized Aircraft	Total Decentralized Aircraft	Total Counted Aircraft	Centralized Counted Aircraft	Decentralized Counted Aircraft	Counted Maneuvering Aircraft	Centralized Counted Maneuvering Aircraft	Decentralized Counted Maneuvering Aircraft
31000203	3	100%	2.00x	10	73.68%	3718	0	3718	3246	0	3246	836	0	836
31000204	4	100%	2.00x	10	74.41%	3644	0	3644	3154	0	3154	689	0	689
31000205	5	100%	2.00x	10	75.80%	3498	0	3498	3058	0	3058	712	0	712
31000301	1	100%	3.00x	10	65.42%	4863	0	4863	4296	0	4296	1389	0	1389
31000302	2	100%	3.00x	10	68.34%	4839	0	4839	4276	0	4276	1219	0	1219
31000303	3	100%	3.00x	10	63.73%	5577	0	5577	4997	0	4997	1693	0	1693
31000304	4	100%	3.00x	10	64.41%	5466	0	5466	4879	0	4879	1541	0	1541
31000305	5	100%	3.00x	10	66.33%	5247	0	5247	4681	0	4681	1455	0	1455
31000401	1	100%	4.00x	10	57.27%	6484	0	6484	5814	0	5814	2205	0	2205
31000402	2	100%	4.00x	10	60.10%	6452	0	6452	5771	0	5771	1963	0	1963
31000403	3	100%	4.00x	10	55.58%	7436	0	7436	6737	0	6737	2636	0	2636
31000404	4	100%	4.00x	10	56.32%	7288	0	7288	6581	0	6581	2465	0	2465
31000405	5	100%	4.00x	10	58.15%	6996	0	6996	6310	0	6310	2251	0	2251
31000501	1	100%	5.00x	10	50.55%	8105	0	8105	7296	0	7296	3019	0	3019
31000502	2	100%	5.00x	10	53.67%	8065	0	8065	7285	0	7285	2742	0	2742
31000504	4	100%	5.00x	10	50.08%	9110	0	9110	8256	0	8256	3338	0	3338
31000505	5	100%	5.00x	10	51.79%	8745	0	8745	7927	0	7927	3137	0	3137
31001201	1	100%	1.25x	10	83.44%	2026	0	2026	1659	0	1659	268	0	268
31001202	2	100%	1.25x	10	86.38%	2016	0	2016	1643	0	1643	200	0	200
31001203	3	100%	1.25x	10	83.44%	2324	0	2324	1927	0	1927	309	0	309
31001204	4	100%	1.25x	10	83.92%	2278	0	2278	1869	0	1869	244	0	244
31001205	5	100%	1.25x	10	84.73%	2186	0	2186	1803	0	1803	286	0	286
31001501	1	100%	1.50x	10	80.10%	2432	0	2432	2041	0	2041	397	0	397
31001502	2	100%	1.50x	10	83.41%	2420	0	2420	2011	0	2011	295	0	295
31001503	3	100%	1.50x	10	79.87%	2789	0	2789	2367	0	2367	468	0	468
31001504	4	100%	1.50x	10	80.71%	2733	0	2733	2297	0	2297	388	0	388
31001505	5	100%	1.50x	10	81.62%	2624	0	2624	2224	0	2224	414	0	414
31001701	1	100%	1.75x	10	77.49%	2837	0	2837	2421	0	2421	530	0	530
31001702	2	100%	1.75x	10	80.37%	2823	0	2823	2383	0	2383	430	0	430
31001703	3	100%	1.75x	10	76.80%	3253	0	3253	2803	0	2803	648	0	648
31001704	4	100%	1.75x	10	77.53%	3189	0	3189	2725	0	2725	564	0	564
31001705	5	100%	1.75x	10	78.78%	3061	0	3061	2629	0	2629	570	0	570
31002501	1	100%	2.50x	10	69.82%	4053	0	4053	3545	0	3545	1006	0	1006
31002502	2	100%	2.50x	10	72.93%	4033	0	4033	3523	0	3523	847	0	847
31002503	3	100%	2.50x	10	68.43%	4648	0	4648	4126	0	4126	1227	0	1227
31002504	4	100%	2.50x	10	69.23%	4555	0	4555	4012	0	4012	1102	0	1102
31002505	5	100%	2.50x	10	70.71%	4373	0	4373	3872	0	3872	1074	0	1074
40000101	1	0%	1.00x	30	78.50%	1621	1621	0	1284	1284	0	104	104	0
40000102	2	0%	1.00x	30	82.80%	1613	1613	0	1271	1271	0	108	108	0
40000103	3	0%	1.00x	30	79.30%	1859	1859	0	1491	1491	0	164	164	0
40000104	4	0%	1.00x	30	79.07%	1822	1822	0	1445	1445	0	111	111	0
40000105	5	0%	1.00x	30	81.04%	1749	1749	0	1391	1391	0	137	137	0
40250101	1	25%	1.00x	30	78.35%	1621	1222	399	1284	963	321	100	67	33
40250102	2	25%	1.00x	30	82.51%	1613	1209	404	1271	957	314	93	70	23
40250103	3	25%	1.00x	30	79.06%	1859	1393	466	1491	1119	372	138	99	39
40250104	4	25%	1.00x	30	78.88%	1822	1368	454	1445	1093	352	100	71	29

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Flexibility (%)	Total Aircraft	Total Centralized Aircraft	Total Decentralized Aircraft	Total Counted Aircraft	Centralized Counted Aircraft	Decentralized Counted Aircraft	Counted Maneuvering Aircraft	Centralized Counted Maneuvering Aircraft	Decentralized Counted Maneuvering Aircraft
40250105	5	25%	1.00x	30	80.75%	1749	1312	437	1391	1040	351	120	73	47
40500101	1	50%	1.00x	30	78.44%	1621	814	807	1284	658	626	103	34	69
40500102	2	50%	1.00x	30	82.67%	1613	800	813	1271	652	619	86	31	55
40500103	3	50%	1.00x	30	78.90%	1859	926	933	1491	743	748	138	46	92
40500104	4	50%	1.00x	30	78.80%	1822	906	916	1445	719	726	95	31	64
40500105	5	50%	1.00x	30	80.76%	1749	872	877	1393	688	705	118	34	84
40750101	1	75%	1.00x	30	78.58%	1621	408	1213	1283	335	948	113	3	110
40750102	2	75%	1.00x	30	82.88%	1613	402	1211	1272	331	941	95	8	87
40750103	3	75%	1.00x	30	79.16%	1859	455	1404	1490	369	1121	153	9	144
40750104	4	75%	1.00x	30	79.06%	1822	449	1373	1444	347	1097	109	10	99
40750105	5	75%	1.00x	30	81.00%	1749	434	1315	1393	338	1055	122	5	117
41000101	1	100%	1.00x	30	79.11%	1621	0	1621	1283	0	1283	137	0	137
41000102	2	100%	1.00x	30	83.04%	1613	0	1613	1272	0	1272	124	0	124
41000103	3	100%	1.00x	30	79.34%	1859	0	1859	1490	0	1490	179	0	179
41000104	4	100%	1.00x	30	79.48%	1822	0	1822	1444	0	1444	146	0	146
41000105	5	100%	1.00x	30	81.41%	1749	0	1749	1393	0	1393	159	0	159
50000101	1	0%	1.00x	300	78.00%	1621	1621	0	1284	1284	0	107	107	0
50000102	2	0%	1.00x	300	82.27%	1613	1613	0	1271	1271	0	108	108	0
50000103	3	0%	1.00x	300	78.56%	1859	1859	0	1491	1491	0	164	164	0
50000104	4	0%	1.00x	300	78.27%	1822	1822	0	1445	1445	0	113	113	0
50000105	5	0%	1.00x	300	80.39%	1749	1749	0	1392	1392	0	140	140	0
50250101	1	25%	1.00x	300	77.78%	1621	1222	399	1284	963	321	103	69	34
50250102	2	25%	1.00x	300	82.01%	1613	1209	404	1271	957	314	94	70	24
50250103	3	25%	1.00x	300	78.31%	1859	1393	466	1490	1118	372	138	99	39
50250104	4	25%	1.00x	300	78.05%	1822	1368	454	1445	1093	352	100	71	29
50250105	5	25%	1.00x	300	80.18%	1749	1312	437	1393	1041	352	125	75	50
50500101	1	50%	1.00x	300	77.87%	1621	814	807	1284	658	626	105	35	70
50500102	2	50%	1.00x	300	82.17%	1613	800	813	1270	651	619	87	31	56
50500103	3	50%	1.00x	300	78.22%	1859	926	933	1491	743	748	140	47	93
50500104	4	50%	1.00x	300	78.00%	1822	906	916	1445	719	726	95	31	64
50500105	5	50%	1.00x	300	80.07%	1749	872	877	1392	688	704	120	36	84
50750101	1	75%	1.00x	300	78.01%	1621	408	1213	1283	335	948	114	3	111
50750102	2	75%	1.00x	300	82.37%	1613	402	1211	1271	331	940	96	9	87
50750103	3	75%	1.00x	300	78.43%	1859	455	1404	1490	369	1121	155	9	146
50750104	4	75%	1.00x	300	78.28%	1822	449	1373	1445	347	1098	111	10	101
50750105	5	75%	1.00x	300	80.29%	1749	434	1315	1392	338	1054	123	5	118
51000101	1	100%	1.00x	300	78.54%	1621	0	1621	1283	0	1283	139	0	139
51000102	2	100%	1.00x	300	82.49%	1613	0	1613	1272	0	1272	124	0	124
51000103	3	100%	1.00x	300	78.70%	1859	0	1859	1491	0	1491	181	0	181
51000104	4	100%	1.00x	300	78.65%	1822	0	1822	1445	0	1445	148	0	148
51000105	5	100%	1.00x	300	80.60%	1749	0	1749	1393	0	1393	161	0	161

Table 3 Cost and delay data

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Estimated Cost (klbm)	Estimated Cost per Aircraft (lbm)	Aircraft Estimated Cost (klbm)	Aircraft Estimated Cost per Aircraft (lbm)	Actual Cost (klbm)	Actual Cost per Aircraft (lbm)	Estimated Delay (min)	Estimated Delay per Aircraft (sec)	Actual Delay (min)	Actual Delay per Aircraft (sec)
10000101	1	0%	1.00x	2	1.016	8.61	1.24	10.47	595.93	5050.23	17.95	9.1	68.27	34.7
10000102	2	0%	1.00x	2	0.553	4.69	0.62	5.22	829.98	7033.73	4.00	2.0	27.34	13.9
10000103	3	0%	1.00x	2	0.141	0.79	0.13	0.70	1054.20	5922.46	11.27	3.8	35.29	11.9
10000104	4	0%	1.00x	2	0.709	5.58	0.79	6.25	809.03	6370.33	18.72	8.8	49.90	23.6
10000105	5	0%	1.00x	2	0.381	2.64	0.46	3.18	369.64	2566.91	3.00	1.3	41.61	17.3
10250101	1	25%	1.00x	2	1.987	16.84	2.06	17.48	603.70	5116.07	36.88	18.8	61.27	31.2
10250102	2	25%	1.00x	2	0.598	5.49	0.63	5.79	1016.93	9329.64	4.00	2.2	29.52	16.3
10250103	3	25%	1.00x	2	0.844	5.08	0.80	4.81	831.20	5007.23	31.62	11.4	52.27	18.9
10250104	4	25%	1.00x	2	0.824	6.98	0.79	6.65	884.95	7499.58	19.29	9.8	45.13	22.9
10250105	5	25%	1.00x	2	1.452	9.81	1.54	10.39	498.72	3369.70	12.20	4.9	53.96	21.9
10500101	1	50%	1.00x	2	2.582	20.99	2.72	22.15	594.08	4829.95	47.81	23.3	56.63	27.6
10500102	2	50%	1.00x	2	1.470	14.00	1.44	13.67	1232.75	11740.45	31.00	17.7	42.80	24.5
10500103	3	50%	1.00x	2	2.386	14.46	2.37	14.39	593.16	3594.90	41.74	15.2	58.85	21.4
10500104	4	50%	1.00x	2	1.017	9.87	0.88	8.53	712.64	6918.79	8.65	5.0	32.92	19.2
10500105	5	50%	1.00x	2	2.079	14.15	2.11	14.34	554.92	3774.99	38.20	15.6	49.38	20.2
10750101	1	75%	1.00x	2	2.549	19.92	2.57	20.08	664.23	5189.28	56.85	26.7	65.43	30.7
10750102	2	75%	1.00x	2	1.535	14.34	1.53	14.27	1280.66	11968.81	28.00	15.7	40.76	22.9
10750103	3	75%	1.00x	2	1.407	8.23	1.37	8.02	585.24	3422.45	49.26	17.3	69.58	24.4
10750104	4	75%	1.00x	2	1.516	12.42	1.51	12.39	933.84	7654.44	35.34	17.4	58.44	28.7
10750105	5	75%	1.00x	2	3.420	23.58	3.43	23.63	601.02	4144.99	59.42	24.6	62.69	25.9
11000101	1	100%	1.00x	2	2.908	21.07	2.91	21.07	623.84	4520.57	58.72	25.5	71.48	31.1
11000102	2	100%	1.00x	2	1.893	16.61	1.89	16.61	1047.00	9184.20	30.00	15.8	42.15	22.2
11000103	3	100%	1.00x	2	3.144	17.37	3.14	17.37	625.09	3453.53	68.85	22.8	74.52	24.7
11000104	4	100%	1.00x	2	1.629	11.47	1.63	11.47	1073.90	7562.69	40.35	17.0	64.34	27.2
11000105	5	100%	1.00x	2	4.820	30.31	4.82	30.31	559.16	3516.75	64.00	24.2	69.57	26.3
20000101	1	0%	1.00x	5	0.201	1.72	0.35	3.00	608.80	5203.44	40.75	20.9	79.62	40.8
20000102	2	0%	1.00x	5	-0.268	-2.39	0.29	2.55	931.12	8313.60	30.75	16.5	65.78	35.2
20000103	3	0%	1.00x	5	-0.309	-1.74	-0.15	-0.82	826.37	4668.77	24.79	8.4	47.82	16.2
20000104	4	0%	1.00x	5	-0.056	-0.43	-0.41	-3.21	1115.12	8644.31	44.67	20.8	84.09	39.1
20000105	5	0%	1.00x	5	-0.073	-0.52	0.18	1.31	389.68	2763.68	45.45	19.3	73.59	31.3
20250101	1	25%	1.00x	5	0.115	1.02	-0.06	-0.51	510.32	4516.08	55.75	29.6	84.91	45.1
20250102	2	25%	1.00x	5	-1.063	-10.22	-0.47	-4.56	1170.97	11259.34	67.01	38.7	88.79	51.2
20250103	3	25%	1.00x	5	0.190	1.17	0.36	2.21	496.96	3067.67	54.04	20.0	76.26	28.2
20250104	4	25%	1.00x	5	0.036	0.30	-0.42	-3.45	1086.43	8905.19	39.47	19.4	80.30	39.5
20250105	5	25%	1.00x	5	-0.222	-1.53	-0.10	-0.72	512.33	3533.29	58.63	24.3	89.85	37.2
20500101	1	50%	1.00x	5	-0.118	-1.01	-0.09	-0.75	437.18	3736.56	63.26	32.4	84.72	43.4
20500102	2	50%	1.00x	5	-0.876	-8.68	-0.57	-5.64	918.07	9089.77	75.71	45.0	95.07	56.5
20500103	3	50%	1.00x	5	0.480	2.93	0.48	2.94	572.69	3491.98	84.27	30.8	104.78	38.3
20500104	4	50%	1.00x	5	0.388	3.70	0.12	1.15	759.64	7234.66	51.72	29.6	77.10	44.1
20500105	5	50%	1.00x	5	-0.372	-2.59	-0.14	-0.97	535.47	3718.56	71.98	30.0	97.67	40.7
20750101	1	75%	1.00x	5	0.589	4.71	0.59	4.75	526.81	4214.48	64.67	31.0	83.27	40.0
20750102	2	75%	1.00x	5	-0.639	-6.08	-0.60	-5.76	1102.99	10504.71	67.79	38.7	93.90	53.7
20750103	3	75%	1.00x	5	0.680	3.98	0.69	4.06	885.27	5177.00	72.27	25.4	94.57	33.2
20750104	4	75%	1.00x	5	0.510	4.52	0.52	4.64	1349.64	11943.73	83.83	44.5	106.70	56.7
20750105	5	75%	1.00x	5	0.006	0.04	0.02	0.13	595.16	4191.24	74.21	31.4	94.90	40.1

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Estimated Cost (klbm)	Estimated Cost per Aircraft (lbm)	Aircraft Estimated Cost (klbm)	Aircraft Estimated Cost per Aircraft (lbm)	Actual Cost (klbm)	Actual Cost per Aircraft (lbm)	Estimated Delay (min)	Estimated Delay per Aircraft (sec)	Actual Delay (min)	Actual Delay per Aircraft (sec)
21000101	1	100%	1.00x	5	0.772	5.56	0.77	5.56	724.94	5215.38	81.29	35.1	99.24	42.8
21000102	2	100%	1.00x	5	-0.027	-0.23	-0.03	-0.23	851.08	7092.34	59.86	29.9	82.25	41.1
21000103	3	100%	1.00x	5	2.586	13.90	2.59	13.90	583.06	3134.72	105.14	33.9	117.28	37.8
21000104	4	100%	1.00x	5	1.066	7.95	1.07	7.95	1211.95	9044.37	98.61	44.2	121.32	54.3
21000105	5	100%	1.00x	5	0.462	2.94	0.46	2.94	559.74	3565.24	64.86	24.8	86.35	33.0
30000101	1	0%	1.00x	10	0.802	7.29	0.96	8.74	640.66	5824.22	47.78	26.1	67.08	36.6
30000102	2	0%	1.00x	10	-0.400	-3.70	-0.46	-4.22	759.54	7032.82	49.32	27.4	88.82	49.3
30000103	3	0%	1.00x	10	-1.196	-6.95	-0.93	-5.40	944.63	5492.02	54.78	19.1	106.08	37.0
30000104	4	0%	1.00x	10	0.335	2.82	0.09	0.73	1130.20	9497.46	48.27	24.3	74.20	37.4
30000105	5	0%	1.00x	10	-0.227	-1.66	-0.11	-0.78	515.46	3762.51	19.49	8.5	49.72	21.8
30250101	1	25%	1.00x	10	0.669	6.55	0.72	7.09	589.01	5774.64	68.95	40.6	84.02	49.4
30250102	2	25%	1.00x	10	-0.723	-7.46	-0.50	-5.14	1139.79	11750.37	59.56	36.8	90.52	56.0
30250103	3	25%	1.00x	10	0.265	1.72	0.23	1.48	719.83	4674.25	72.72	28.3	94.18	36.7
30250104	4	25%	1.00x	10	0.116	1.10	-0.07	-0.65	943.66	8902.46	34.74	19.7	60.30	34.1
30250105	5	25%	1.00x	10	-0.276	-2.17	-0.38	-2.95	559.86	4408.36	38.48	18.2	68.53	32.4
30500101	1	50%	1.00x	10	0.148	1.37	0.38	3.56	450.74	4173.55	87.44	48.6	103.96	57.8
30500102	2	50%	1.00x	10	-0.730	-8.21	-0.61	-6.86	1062.14	11934.19	57.57	38.8	79.65	53.7
30500103	3	50%	1.00x	10	-1.322	-8.81	-1.33	-8.88	607.85	4052.34	73.38	29.4	96.66	38.7
30500104	4	50%	1.00x	10	0.267	2.70	0.14	1.41	1223.89	12362.49	36.77	22.3	63.47	38.5
30500105	5	50%	1.00x	10	0.134	1.07	0.03	0.27	620.01	4920.69	49.32	23.5	76.05	36.2
30750101	1	75%	1.00x	10	0.085	0.73	0.10	0.89	820.08	7009.27	102.14	52.4	124.64	63.9
30750102	2	75%	1.00x	10	-0.729	-7.59	-0.74	-7.70	1089.17	11345.48	56.62	35.4	79.21	49.5
30750103	3	75%	1.00x	10	-0.795	-4.88	-0.79	-4.86	870.91	5342.98	83.23	30.6	105.36	38.8
30750104	4	75%	1.00x	10	0.165	1.51	0.19	1.76	1094.36	10039.96	64.52	35.5	90.41	49.8
30750105	5	75%	1.00x	10	0.076	0.60	0.09	0.72	621.22	4891.52	70.59	33.3	93.75	44.3
31000101	1	100%	1.00x	10	-0.035	-0.25	-0.04	-0.25	748.69	5347.80	118.09	50.6	144.08	61.7
31000102	2	100%	1.00x	10	-0.859	-6.98	-0.86	-6.98	1102.60	8964.22	67.94	33.1	117.93	57.5
31000103	3	100%	1.00x	10	-0.568	-3.10	-0.57	-3.10	666.06	3639.65	124.06	40.7	144.36	47.3
31000104	4	100%	1.00x	10	0.375	2.72	0.38	2.72	1221.13	8848.74	122.89	53.4	143.89	62.6
31000105	5	100%	1.00x	10	0.205	1.28	0.21	1.28	601.23	3757.67	76.83	28.8	99.98	37.5
31000201	1	100%	2.00x	10	3.968	5.93	3.97	5.93	2902.77	4338.97	530.00	47.5	536.39	48.1
31000202	2	100%	2.00x	10	2.446	4.38	2.45	4.38	699.13	1252.92	443.31	47.7	463.86	49.9
31000203	3	100%	2.00x	10	7.636	9.13	7.64	9.13	1995.59	2387.07	616.89	44.3	625.04	44.9
31000204	4	100%	2.00x	10	2.038	2.96	2.04	2.96	7746.54	11243.16	522.24	45.5	551.77	48.1
31000205	5	100%	2.00x	10	9.013	12.66	9.01	12.66	1358.78	1908.39	571.06	48.1	565.47	47.7
31000301	1	100%	3.00x	10	17.131	12.33	17.13	12.33	3431.77	2470.67	1289.42	55.7	1239.85	53.6
31000302	2	100%	3.00x	10	3.497	2.87	3.50	2.87	695.34	570.42	1071.38	52.7	1074.05	52.9
31000303	3	100%	3.00x	10	34.534	20.40	34.53	20.40	2990.13	1766.17	1531.56	54.3	1463.22	51.9
31000304	4	100%	3.00x	10	17.249	11.19	17.25	11.19	19004.24	12332.41	1291.95	50.3	1282.03	49.9
31000305	5	100%	3.00x	10	21.914	15.06	21.91	15.06	2525.97	1736.06	1345.37	55.5	1279.00	52.7
31000401	1	100%	4.00x	10	59.139	26.82	59.14	26.82	5261.10	2385.99	2320.73	63.1	2134.87	58.1
31000402	2	100%	4.00x	10	21.092	10.74	21.09	10.74	3257.02	1659.20	1854.14	56.7	1800.68	55.0
31000403	3	100%	4.00x	10	81.268	30.83	81.27	30.83	3550.40	1346.89	2927.96	66.6	2641.39	60.1
31000404	4	100%	4.00x	10	68.186	27.66	68.19	27.66	21404.77	8683.48	2858.46	69.6	2660.51	64.8
31000405	5	100%	4.00x	10	53.227	23.65	53.23	23.65	3359.33	1492.37	2326.86	62.0	2161.81	57.6
31000501	1	100%	5.00x	10	111.160	36.82	111.16	36.82	6604.65	2187.70	3715.76	73.8	3350.37	66.6

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31000502	2	100%	5.00x	10	68.902	25.13	68.90	25.13	3899.92	1422.29	3113.58	68.1	2849.50	62.4
31000504	4	100%	5.00x	10	105.683	31.66	105.68	31.66	24932.60	7469.32	4047.52	72.8	3758.48	67.6
31000505	5	100%	5.00x	10	115.012	36.66	115.01	36.66	5327.45	1698.26	3458.30	66.1	3173.26	60.7
31001201	1	100%	1.25x	10	0.138	0.51	0.14	0.51	1675.55	6252.06	203.87	45.6	229.78	51.4
31001202	2	100%	1.25x	10	-1.163	-5.82	-1.16	-5.82	886.19	4430.93	124.89	37.5	153.88	46.2
31001203	3	100%	1.25x	10	0.079	0.26	0.08	0.26	884.25	2861.65	193.35	37.5	214.44	41.6
31001204	4	100%	1.25x	10	1.652	6.77	1.65	6.77	1347.28	5521.65	195.42	48.1	219.23	53.9
31001205	5	100%	1.25x	10	1.701	5.95	1.70	5.95	748.41	2616.81	137.04	28.7	158.14	33.2
31001501	1	100%	1.50x	10	1.295	3.26	1.29	3.26	2177.16	5484.02	281.13	42.5	312.17	47.2
31001502	2	100%	1.50x	10	1.650	5.59	1.65	5.59	1032.81	3501.04	225.44	45.9	240.04	48.8
31001503	3	100%	1.50x	10	5.682	12.14	5.68	12.14	1358.56	2902.90	319.36	40.9	315.78	40.5
31001504	4	100%	1.50x	10	1.274	3.28	1.27	3.28	853.87	2200.70	305.50	47.2	336.56	52.0
31001505	5	100%	1.50x	10	0.959	2.32	0.96	2.32	934.19	2256.51	260.88	37.8	286.38	41.5
31001701	1	100%	1.75x	10	0.598	1.13	0.60	1.13	1851.55	3493.48	449.35	50.9	480.26	54.4
31001702	2	100%	1.75x	10	0.584	1.36	0.58	1.36	536.75	1248.25	361.07	50.4	362.13	50.5
31001703	3	100%	1.75x	10	5.452	8.41	5.45	8.41	1301.84	2009.01	507.67	47.0	503.33	46.6
31001704	4	100%	1.75x	10	1.159	2.06	1.16	2.06	1022.67	1813.24	411.43	43.8	438.16	46.6
31001705	5	100%	1.75x	10	1.421	2.49	1.42	2.49	999.00	1752.64	385.24	40.6	408.55	43.0
31002501	1	100%	2.50x	10	11.169	11.10	11.17	11.10	3629.56	3607.91	892.94	53.3	858.67	51.2
31002502	2	100%	2.50x	10	2.851	3.37	2.85	3.37	688.09	812.38	726.65	51.5	733.63	52.0
31002503	3	100%	2.50x	10	13.525	11.02	13.52	11.02	2533.93	2065.14	1084.81	53.0	1067.02	52.2
31002504	4	100%	2.50x	10	8.338	7.57	8.34	7.57	7119.04	6460.11	863.56	47.0	874.41	47.6
31002505	5	100%	2.50x	10	15.828	14.74	15.83	14.74	2326.52	2166.22	951.63	53.2	908.51	50.8
40000101	1	0%	1.00x	30	0.412	3.97	0.45	4.31	731.99	7038.39	32.09	18.5	55.19	31.8
40000102	2	0%	1.00x	30	-0.235	-2.18	-0.53	-4.91	731.75	6775.43	41.75	23.2	64.07	35.6
40000103	3	0%	1.00x	30	1.381	8.42	1.58	9.65	892.57	5442.52	59.41	21.7	83.51	30.6
40000104	4	0%	1.00x	30	0.812	7.31	0.96	8.69	1196.44	10778.75	61.05	33.0	87.95	47.5
40000105	5	0%	1.00x	30	1.022	7.46	1.20	8.76	451.82	3297.96	44.89	19.7	75.78	33.2
40250101	1	25%	1.00x	30	0.139	1.39	0.40	3.99	628.39	6283.90	62.60	37.6	85.71	51.4
40250102	2	25%	1.00x	30	-0.458	-4.92	-0.42	-4.46	1015.03	10914.30	42.34	27.3	63.90	41.2
40250103	3	25%	1.00x	30	1.205	8.74	1.48	10.75	904.48	6554.17	63.70	27.7	87.28	37.9
40250104	4	25%	1.00x	30	0.404	4.04	0.51	5.09	941.57	9415.70	45.33	27.2	72.16	43.3
40250105	5	25%	1.00x	30	0.043	0.36	-0.30	-2.48	382.91	3190.93	52.45	26.2	76.72	38.4
40500101	1	50%	1.00x	30	-0.209	-2.03	-0.03	-0.28	542.42	5266.17	65.71	38.3	90.87	52.9
40500102	2	50%	1.00x	30	-0.791	-9.20	-0.72	-8.36	1156.34	13445.80	46.33	32.3	77.56	54.1
40500103	3	50%	1.00x	30	0.096	0.70	0.09	0.67	723.96	5246.07	58.32	25.4	77.17	33.6
40500104	4	50%	1.00x	30	0.290	3.06	0.34	3.59	1379.86	14524.81	44.02	27.8	70.66	44.6
40500105	5	50%	1.00x	30	-0.426	-3.61	-0.63	-5.38	530.53	4496.04	52.01	26.4	77.14	39.2
40750101	1	75%	1.00x	30	-0.748	-6.62	-0.73	-6.44	740.11	6549.65	84.35	44.8	110.64	58.7
40750102	2	75%	1.00x	30	-0.826	-8.69	-0.84	-8.83	1081.46	11383.82	40.73	25.7	85.46	54.0
40750103	3	75%	1.00x	30	-0.177	-1.15	-0.18	-1.18	409.50	2676.44	88.97	34.9	112.22	44.0
40750104	4	75%	1.00x	30	0.343	3.15	0.41	3.73	1491.86	13686.75	80.48	44.3	106.66	58.7
40750105	5	75%	1.00x	30	-0.439	-3.60	-0.44	-3.62	483.64	3964.27	85.29	41.9	109.14	53.7
41000101	1	100%	1.00x	30	-0.953	-6.96	-0.95	-6.96	519.96	3795.36	95.59	41.9	122.23	53.5
41000102	2	100%	1.00x	30	-1.192	-9.61	-1.19	-9.61	1286.56	10375.51	56.48	27.3	104.82	50.7
41000103	3	100%	1.00x	30	-0.600	-3.35	-0.60	-3.35	804.97	4497.02	125.64	42.1	148.34	49.7

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41000104	4	100%	1.00x	30	0.141	0.97	0.14	0.97	1386.30	9495.24	120.92	49.7	147.89	60.8
41000105	5	100%	1.00x	30	-0.339	-2.13	-0.34	-2.13	556.51	3500.08	101.41	38.3	125.89	47.5
50000101	1	0%	1.00x	300	0.598	5.59	0.50	4.70	758.47	7088.47	29.67	16.6	53.87	30.2
50000102	2	0%	1.00x	300	-0.200	-1.85	-0.42	-3.86	728.08	6741.49	36.91	20.5	65.46	36.4
50000103	3	0%	1.00x	300	1.546	9.43	1.66	10.13	1208.74	7370.37	73.54	26.9	97.28	35.6
50000104	4	0%	1.00x	300	0.828	7.32	1.15	10.16	1018.54	9013.60	66.24	35.2	92.92	49.3
50000105	5	0%	1.00x	300	0.501	3.58	0.09	0.61	449.22	3208.72	43.39	18.6	70.63	30.3
50250101	1	25%	1.00x	300	0.015	0.15	0.13	1.26	656.29	6371.77	59.52	34.7	82.15	47.9
50250102	2	25%	1.00x	300	-0.401	-4.26	-0.31	-3.28	1227.93	13063.13	38.84	24.8	60.48	38.6
50250103	3	25%	1.00x	300	0.844	6.11	1.24	9.00	544.36	3944.64	57.58	25.0	81.06	35.2
50250104	4	25%	1.00x	300	0.323	3.23	0.59	5.92	1180.50	11804.96	43.66	26.2	70.60	42.4
50250105	5	25%	1.00x	300	-0.038	-0.31	-0.46	-3.70	353.54	2828.29	58.59	28.1	89.80	43.1
50500101	1	50%	1.00x	300	0.155	1.47	0.32	3.07	672.99	6409.40	72.87	41.6	89.28	51.0
50500102	2	50%	1.00x	300	-0.595	-6.84	-0.55	-6.33	1138.37	13084.76	41.35	28.5	63.80	44.0
50500103	3	50%	1.00x	300	-0.109	-0.78	-0.07	-0.50	759.90	5427.85	53.74	23.0	72.15	30.9
50500104	4	50%	1.00x	300	0.307	3.23	0.36	3.80	1414.79	14892.51	41.75	26.4	69.00	43.6
50500105	5	50%	1.00x	300	-0.348	-2.90	-0.64	-5.32	426.79	3556.57	58.58	29.3	89.68	44.8
50750101	1	75%	1.00x	300	-0.770	-6.75	-0.75	-6.58	741.94	6508.25	87.22	45.9	112.51	59.2
50750102	2	75%	1.00x	300	-0.643	-6.69	-0.66	-6.88	1036.43	10796.15	35.86	22.4	61.50	38.4
50750103	3	75%	1.00x	300	-0.527	-3.40	-0.53	-3.43	602.51	3887.15	82.34	31.9	105.60	40.9
50750104	4	75%	1.00x	300	0.313	2.82	0.38	3.44	1437.46	12950.07	80.46	43.5	107.21	58.0
50750105	5	75%	1.00x	300	-0.192	-1.56	-0.19	-1.58	518.10	4212.22	98.61	48.1	127.84	62.4
51000101	1	100%	1.00x	300	-0.913	-6.57	-0.91	-6.57	684.94	4927.59	96.09	41.5	123.96	53.5
51000102	2	100%	1.00x	300	-0.967	-7.80	-0.97	-7.80	1180.66	9521.41	51.61	25.0	98.40	47.6
51000103	3	100%	1.00x	300	-0.846	-4.67	-0.85	-4.67	664.53	3671.41	118.05	39.1	140.55	46.6
51000104	4	100%	1.00x	300	0.113	0.77	0.11	0.77	1014.40	6854.04	124.19	50.3	151.13	61.3
51000105	5	100%	1.00x	300	-0.527	-3.27	-0.53	-3.27	493.33	3064.16	94.90	35.4	124.52	46.4

Table 4 Fuel data

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Original Estimated Fuel (klbm)	Original Estimated Fuel per Aircraft (lbm)	Estimated Fuel (klbm)	Estimated Fuel per Aircraft (lbm)	Actual Fuel (klbm)	Actual Fuel per Aircraft (lbm)
10000101	1	0%	1.00x	2	2128.754	18040.286	2130.005	18050.892	12185.810	103269.575
10000102	2	0%	1.00x	2	1839.376	15587.934	1840.254	15595.374	11001.491	93232.972
10000103	3	0%	1.00x	2	2356.867	13240.825	2356.799	13240.442	13282.441	74620.454
10000104	4	0%	1.00x	2	2193.138	17268.807	2193.800	17274.015	12618.763	99360.340
10000105	5	0%	1.00x	2	1992.701	13838.204	1993.328	13842.556	11647.714	80886.903
10250101	1	25%	1.00x	2	2122.011	17983.146	2124.355	18003.009	12152.648	102988.542
10250102	2	25%	1.00x	2	1839.376	16875.012	1840.265	16883.166	11001.642	100932.498
10250103	3	25%	1.00x	2	2356.867	14197.993	2357.886	14204.134	13282.463	80014.835
10250104	4	25%	1.00x	2	2192.029	18576.521	2193.040	18585.085	12604.977	106821.841

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Original Estimated Fuel (klbm)	Original Estimated Fuel per Aircraft (lbm)	Estimated Fuel (klbm)	Estimated Fuel per Aircraft (lbm)	Actual Fuel (klbm)	Actual Fuel per Aircraft (lbm)
10250105	5	25%	1.00x	2	1993.636	13470.515	1995.513	13483.196	11649.530	78713.040
10500101	1	50%	1.00x	2	2123.962	17267.981	2127.196	17294.276	12158.080	98846.182
10500102	2	50%	1.00x	2	1838.932	17513.634	1840.150	17525.234	11000.979	104771.225
10500103	3	50%	1.00x	2	2355.621	14276.492	2357.634	14288.691	13281.198	80492.109
10500104	4	50%	1.00x	2	2193.138	21292.607	2194.591	21306.711	12619.425	122518.690
10500105	5	50%	1.00x	2	1993.636	13562.151	1996.163	13579.337	11650.291	79253.677
10750101	1	75%	1.00x	2	2123.962	16593.451	2126.961	16616.886	12158.133	94985.414
10750102	2	75%	1.00x	2	1838.203	17179.464	1839.920	17195.514	11000.522	102808.614
10750103	3	75%	1.00x	2	2355.479	13774.733	2356.831	13782.637	13280.754	77665.229
10750104	4	75%	1.00x	2	2193.138	17976.545	2195.115	17992.744	12619.403	103437.729
10750105	5	75%	1.00x	2	1992.701	13742.768	1996.647	13769.978	11649.373	80340.501
11000101	1	100%	1.00x	2	2123.887	15390.488	2127.380	15415.799	12157.880	88100.581
11000102	2	100%	1.00x	2	1838.203	16124.585	1840.471	16144.484	11001.035	96500.311
11000103	3	100%	1.00x	2	2355.479	13013.698	2358.634	13031.129	13281.072	73376.089
11000104	4	100%	1.00x	2	2192.029	15436.827	2194.203	15452.134	12606.082	88775.222
11000105	5	100%	1.00x	2	1992.701	12532.713	1998.386	12568.467	11651.311	73278.684
20000101	1	0%	1.00x	5	2123.962	18153.519	2122.661	18142.402	12154.014	103880.459
20000102	2	0%	1.00x	5	1839.450	16423.660	1837.813	16409.046	10999.196	98207.110
20000103	3	0%	1.00x	5	2356.867	13315.632	2354.831	13304.128	13279.235	75023.924
20000104	4	0%	1.00x	5	2193.138	17001.074	2191.582	16989.011	12615.954	97798.094
20000105	5	0%	1.00x	5	1993.636	14139.264	1991.815	14126.348	11646.308	82597.926
20250101	1	25%	1.00x	5	2123.962	18796.121	2123.010	18787.697	12154.407	107561.123
20250102	2	25%	1.00x	5	1839.450	17687.019	1837.017	17663.629	10998.689	105756.627
20250103	3	25%	1.00x	5	2356.725	14547.685	2355.062	14537.420	13278.535	81966.267
20250104	4	25%	1.00x	5	2192.029	17967.455	2190.848	17957.771	12602.355	103297.990
20250105	5	25%	1.00x	5	1993.636	13749.215	1991.172	13732.222	11645.577	80314.324
20500101	1	50%	1.00x	5	2123.962	18153.519	2123.366	18148.425	12155.261	103891.122
20500102	2	50%	1.00x	5	1839.450	18212.376	1837.461	18192.679	10998.226	108893.325
20500103	3	50%	1.00x	5	2356.867	14371.139	2355.615	14363.504	13279.316	80971.440
20500104	4	50%	1.00x	5	2192.029	20876.471	2191.337	20869.880	12603.266	120031.106
20500105	5	50%	1.00x	5	1993.636	13844.696	1991.155	13827.464	11646.029	80875.202
20750101	1	75%	1.00x	5	2123.962	16991.694	2124.087	16992.693	12155.877	97247.019
20750102	2	75%	1.00x	5	1839.450	17518.571	1838.124	17505.941	10998.420	104746.859
20750103	3	75%	1.00x	5	2356.725	13782.017	2356.152	13778.669	13279.746	77659.332
20750104	4	75%	1.00x	5	2191.153	19390.731	2190.609	19385.921	12602.338	111525.119
20750105	5	75%	1.00x	5	1993.089	14035.835	1991.773	14026.568	11646.740	82019.293
21000101	1	100%	1.00x	5	2123.962	15280.300	2124.273	15282.542	12156.495	87456.798
21000102	2	100%	1.00x	5	1839.450	15328.749	1838.996	15324.967	10999.384	91661.530
21000103	3	100%	1.00x	5	2356.867	12671.327	2358.144	12678.195	13280.100	71398.386
21000104	4	100%	1.00x	5	2191.153	16351.885	2191.363	16353.458	12602.810	94050.824
21000105	5	100%	1.00x	5	1993.089	12694.832	1992.839	12693.240	11648.343	74193.265
30000101	1	0%	1.00x	10	2123.931	19308.461	2123.055	19300.498	12155.118	110501.074
30000102	2	0%	1.00x	10	1839.450	17031.944	1837.024	17009.485	10997.770	101831.205
30000103	3	0%	1.00x	10	2355.238	13693.242	2350.089	13663.306	13262.621	77108.262
30000104	4	0%	1.00x	10	2192.029	18420.416	2190.795	18410.046	12602.305	105901.724
30000105	5	0%	1.00x	10	1993.636	14552.089	1992.423	14543.231	11647.652	85019.360

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Original Estimated Fuel (klbm)	Original Estimated Fuel per Aircraft (lbm)	Estimated Fuel (klbm)	Estimated Fuel per Aircraft (lbm)	Actual Fuel (klbm)	Actual Fuel per Aircraft (lbm)
30250101	1	25%	1.00x	10	2123.962	20823.154	2123.346	20817.116	12154.790	119164.605
30250102	2	25%	1.00x	10	1839.450	18963.401	1837.222	18940.429	10997.998	113381.420
30250103	3	25%	1.00x	10	2356.867	15304.330	2355.481	15295.332	13279.343	86229.499
30250104	4	25%	1.00x	10	2192.029	20679.524	2190.909	20668.950	12602.560	118892.080
30250105	5	25%	1.00x	10	1993.636	15697.923	1991.568	15681.639	11646.475	91704.528
30500101	1	50%	1.00x	10	2123.962	19666.312	2122.902	19656.498	12154.196	112538.851
30500102	2	50%	1.00x	10	1839.450	20667.977	1837.707	20648.395	10998.290	123576.295
30500103	3	50%	1.00x	10	2356.867	15712.445	2353.506	15690.038	13277.777	88518.513
30500104	4	50%	1.00x	10	2192.029	22141.712	2191.461	22135.968	12603.216	127305.214
30500105	5	50%	1.00x	10	1992.701	15815.091	1991.567	15806.086	11646.679	92433.959
30750101	1	75%	1.00x	10	2123.500	18149.576	2122.130	18137.866	12153.654	103877.381
30750102	2	75%	1.00x	10	1839.450	19160.937	1837.920	19145.003	10998.292	114565.544
30750103	3	75%	1.00x	10	2355.238	14449.310	2352.519	14432.635	13267.650	81396.623
30750104	4	75%	1.00x	10	2192.029	20110.362	2191.262	20103.320	12603.136	115625.100
30750105	5	75%	1.00x	10	1992.701	15690.562	1991.783	15683.334	11646.501	91704.734
31000101	1	100%	1.00x	10	2123.500	15167.860	2122.135	15158.107	12154.148	86815.341
31000102	2	100%	1.00x	10	1839.570	14955.852	1837.667	14940.385	10998.139	89415.765
31000103	3	100%	1.00x	10	2355.238	12870.151	2352.261	12853.883	13266.766	72495.989
31000104	4	100%	1.00x	10	2192.029	15884.272	2190.871	15875.877	12601.822	91317.548
31000105	5	100%	1.00x	10	1993.636	12460.226	1992.600	12453.751	11648.008	72800.051
31000201	1	100%	2.00x	10	4354.378	6508.786	4351.626	6504.672	30648.866	45812.953
31000202	2	100%	2.00x	10	3688.387	6610.013	3683.246	6600.800	26831.265	48084.705
31000203	3	100%	2.00x	10	5028.495	6014.946	5029.180	6015.765	37318.685	44639.576
31000204	4	100%	2.00x	10	4590.815	6663.011	4585.465	6655.246	34010.655	49362.345
31000205	5	100%	2.00x	10	4182.993	5874.991	4184.755	5877.465	30950.872	43470.326
31000301	1	100%	3.00x	10	6702.682	4825.545	6704.525	4826.872	50399.687	36284.872
31000302	2	100%	3.00x	10	5668.784	4650.356	5656.667	4640.416	44292.956	36335.485
31000303	3	100%	3.00x	10	7456.306	4404.197	7470.519	4412.593	59235.826	34988.675
31000304	4	100%	3.00x	10	7043.610	4570.805	7048.187	4573.775	56063.193	36381.046
31000305	5	100%	3.00x	10	6278.902	4315.396	6286.483	4320.607	50504.666	34711.111
31000401	1	100%	4.00x	10	8997.589	4080.539	9037.487	4098.633	70404.425	31929.445
31000402	2	100%	4.00x	10	7772.664	3959.584	7772.198	3959.347	63529.043	32363.241
31000403	3	100%	4.00x	10	9968.195	3781.561	10026.438	3803.656	81376.820	30871.328
31000404	4	100%	4.00x	10	9456.172	3836.175	9501.649	3854.624	78917.236	32015.106
31000405	5	100%	4.00x	10	8449.956	3753.868	8479.492	3766.989	70999.147	31541.158
31000501	1	100%	5.00x	10	11275.644	3734.894	11366.136	3764.868	89870.273	29768.226
31000502	2	100%	5.00x	10	9799.007	3573.672	9839.898	3588.584	81569.713	29748.254
31000504	4	100%	5.00x	10	11936.462	3575.932	12013.576	3599.034	101757.462	30484.560
31000505	5	100%	5.00x	10	10697.315	3410.046	10789.925	3439.568	91027.956	29017.519
31001201	1	100%	1.25x	10	2696.001	10059.705	2694.086	10052.560	16988.593	63390.274
31001202	2	100%	1.25x	10	2297.073	11485.366	2294.615	11473.076	15031.753	75158.765
31001203	3	100%	1.25x	10	3006.448	9729.607	3003.980	9721.617	19095.187	61796.721
31001204	4	100%	1.25x	10	2778.385	11386.826	2777.517	11383.266	17912.807	73413.143
31001205	5	100%	1.25x	10	2467.073	8626.128	2466.728	8624.923	15870.915	55492.711
31001501	1	100%	1.50x	10	3233.338	8144.427	3231.382	8139.501	21484.536	54117.219
31001502	2	100%	1.50x	10	2744.479	9303.319	2743.953	9301.536	18810.362	63763.938

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Original Estimated Fuel (klbm)	Original Estimated Fuel per Aircraft (lbm)	Estimated Fuel (klbm)	Estimated Fuel per Aircraft (lbm)	Actual Fuel (klbm)	Actual Fuel per Aircraft (lbm)
31001503	3	100%	1.50x	10	3659.026	7818.432	3659.680	7819.829	25319.674	54101.867
31001504	4	100%	1.50x	10	3360.861	8662.013	3358.324	8655.474	23422.077	60366.178
31001505	5	100%	1.50x	10	3068.880	7412.753	3065.771	7405.245	21216.557	51247.723
31001701	1	100%	1.75x	10	3827.525	7221.745	3823.294	7213.762	25286.405	47710.198
31001702	2	100%	1.75x	10	3226.908	7504.438	3223.522	7496.563	22116.447	51433.598
31001703	3	100%	1.75x	10	4261.726	6576.737	4260.493	6574.835	29396.468	45364.919
31001704	4	100%	1.75x	10	4003.626	7098.628	3999.957	7092.123	27904.713	49476.442
31001705	5	100%	1.75x	10	3588.330	6295.317	3583.899	6287.542	24967.955	43803.429
31002501	1	100%	2.50x	10	5528.146	5495.175	5530.464	5497.479	40448.939	40207.693
31002502	2	100%	2.50x	10	4659.217	5500.846	4651.283	5491.479	35353.738	41739.951
31002503	3	100%	2.50x	10	6240.886	5086.296	6238.416	5084.284	48144.690	39237.726
31002504	4	100%	2.50x	10	5798.309	5261.623	5796.355	5259.850	45285.439	41093.865
31002505	5	100%	2.50x	10	5206.102	4847.395	5209.321	4850.392	40368.476	37587.035
40000101	1	0%	1.00x	30	2123.962	20422.709	2122.961	20413.084	12155.274	116877.631
40000102	2	0%	1.00x	30	1839.450	17031.944	1837.175	17010.880	10998.361	101836.676
40000103	3	0%	1.00x	30	2356.867	14371.139	2355.560	14363.173	13279.685	80973.686
40000104	4	0%	1.00x	30	2193.138	19758.004	2192.297	19750.423	12617.040	113667.029
40000105	5	0%	1.00x	30	1992.296	14542.309	1991.733	14538.194	11647.340	85017.078
40250101	1	25%	1.00x	30	2123.962	21239.617	2122.760	21227.602	12154.974	121549.736
40250102	2	25%	1.00x	30	1839.450	19779.032	1837.632	19759.481	10998.748	118266.106
40250103	3	25%	1.00x	30	2356.867	17078.745	2355.734	17070.538	13279.476	96228.085
40250104	4	25%	1.00x	30	2193.138	21931.385	2192.018	21920.175	12616.824	126168.237
40250105	5	25%	1.00x	30	1992.296	16602.469	1990.396	16586.631	11645.324	97044.368
40500101	1	50%	1.00x	30	2123.962	20620.987	2122.862	20610.307	12155.032	118010.021
40500102	2	50%	1.00x	30	1839.450	21388.953	1837.761	21369.308	10998.775	127892.727
40500103	3	50%	1.00x	30	2356.867	17078.745	2354.920	17064.640	13278.595	96221.705
40500104	4	50%	1.00x	30	2193.138	23085.668	2192.545	23079.419	12617.313	132813.823
40500105	5	50%	1.00x	30	1993.636	16895.222	1991.812	16879.767	11647.353	98706.382
40750101	1	75%	1.00x	30	2123.500	18792.039	2121.955	18778.361	12153.990	107557.433
40750102	2	75%	1.00x	30	1839.570	19363.892	1838.023	19347.608	10999.082	115779.813
40750103	3	75%	1.00x	30	2356.725	15403.431	2355.039	15392.410	13279.119	86791.627
40750104	4	75%	1.00x	30	2192.099	20111.003	2191.345	20104.081	12613.255	115717.937
40750105	5	75%	1.00x	30	1993.636	16341.280	1991.304	16322.166	11646.499	95463.104
41000101	1	100%	1.00x	30	2123.500	15500.003	2121.672	15486.655	12153.960	88715.035
41000102	2	100%	1.00x	30	1839.570	14835.240	1837.107	14815.379	10998.205	88695.204
41000103	3	100%	1.00x	30	2356.725	13166.061	2354.166	13151.765	13277.931	74178.385
41000104	4	100%	1.00x	30	2192.099	15014.379	2190.401	15002.749	12612.120	86384.387
41000105	5	100%	1.00x	30	1993.636	12538.593	1991.076	12522.488	11646.374	73247.638
50000101	1	0%	1.00x	300	2123.962	19850.109	2123.560	19846.352	12156.057	113608.014
50000102	2	0%	1.00x	300	1839.450	17031.944	1837.557	17014.414	10998.837	101841.086
50000103	3	0%	1.00x	300	2356.867	14371.139	2355.090	14360.303	13279.050	80969.816
50000104	4	0%	1.00x	300	2193.138	19408.305	2192.099	19399.103	12616.720	111652.394
50000105	5	0%	1.00x	300	1992.701	14233.582	1991.632	14225.941	11646.920	83192.284
50250101	1	25%	1.00x	300	2123.962	20620.987	2122.858	20610.272	12155.178	118011.436
50250102	2	25%	1.00x	300	1839.450	19568.616	1837.969	19552.862	10999.109	117011.802
50250103	3	25%	1.00x	300	2356.725	17077.717	2355.495	17068.802	13279.186	96225.989

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Original Estimated Fuel (klbm)	Original Estimated Fuel per Aircraft (lbm)	Estimated Fuel (klbm)	Estimated Fuel per Aircraft (lbm)	Actual Fuel (klbm)	Actual Fuel per Aircraft (lbm)
50250104	4	25%	1.00x	300	2193.138	21931.385	2191.802	21918.018	12616.594	126165.941
50250105	5	25%	1.00x	300	1993.636	15949.090	1991.027	15928.220	11646.635	93173.078
50500101	1	50%	1.00x	300	2123.962	20228.207	2123.389	20222.752	12155.153	115763.366
50500102	2	50%	1.00x	300	1839.376	21142.256	1838.033	21126.811	10999.143	126426.936
50500103	3	50%	1.00x	300	2356.867	16834.763	2354.692	16819.226	13278.603	94847.167
50500104	4	50%	1.00x	300	2193.138	23085.668	2192.838	23082.508	12617.704	132817.941
50500105	5	50%	1.00x	300	1992.701	16605.845	1991.017	16591.812	11646.335	97052.792
50750101	1	75%	1.00x	300	2123.500	18627.197	2121.853	18612.748	12153.893	106613.098
50750102	2	75%	1.00x	300	1839.450	19160.937	1838.172	19147.627	10999.295	114575.985
50750103	3	75%	1.00x	300	2356.725	15204.677	2354.899	15192.895	13279.112	85671.690
50750104	4	75%	1.00x	300	2193.138	19758.004	2192.586	19753.023	12617.478	113670.972
50750105	5	75%	1.00x	300	1992.701	16200.825	1991.112	16187.902	11646.045	94683.293
51000101	1	100%	1.00x	300	2123.500	15276.981	2121.651	15263.674	12154.050	87439.209
51000102	2	100%	1.00x	300	1839.570	14835.240	1837.438	14818.050	10998.624	88698.578
51000103	3	100%	1.00x	300	2356.867	13021.364	2354.381	13007.630	13278.359	73361.097
51000104	4	100%	1.00x	300	2193.138	14818.503	2191.657	14808.493	12616.344	85245.568
51000105	5	100%	1.00x	300	1993.636	12382.834	1991.144	12367.352	11646.619	72339.251

Table 5 Maneuver, conflict, CD&R invokes, unresolved conflict, and loss of separation data

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Maneuvers	Maneuvers per Aircraft	Conflicts	Conflicts per Aircraft	CD&R Invokes	Unresolved Conflicts	Unresolved Conflicts (%)	Unresolved Conflict Losses	Unresolved Conflict Losses (%)	Losses of Separation	Losses of Separation (%)
10000101	1	0%	1.00x	2	169	0.132	255	0.198	237	88	35%	82	32%	12	5%
10000102	2	0%	1.00x	2	143	0.113	174	0.137	168	30	17%	29	17%	6	3%
10000103	3	0%	1.00x	2	222	0.149	283	0.190	240	51	18%	48	17%	15	5%
10000104	4	0%	1.00x	2	171	0.118	257	0.178	228	74	29%	73	28%	15	6%
10000105	5	0%	1.00x	2	188	0.135	248	0.178	212	48	19%	48	19%	8	3%
10250101	1	25%	1.00x	2	159	0.124	264	0.206	247	83	31%	76	29%	13	5%
10250102	2	25%	1.00x	2	130	0.102	172	0.135	172	34	20%	34	20%	4	2%
10250103	3	25%	1.00x	2	200	0.134	283	0.190	247	51	18%	50	18%	16	6%
10250104	4	25%	1.00x	2	154	0.107	255	0.177	234	82	32%	80	31%	15	6%
10250105	5	25%	1.00x	2	179	0.128	248	0.178	215	36	15%	36	15%	8	3%
10500101	1	50%	1.00x	2	161	0.125	265	0.206	248	74	28%	71	27%	11	4%
10500102	2	50%	1.00x	2	131	0.103	178	0.140	170	30	17%	28	16%	7	4%
10500103	3	50%	1.00x	2	206	0.138	280	0.188	243	34	12%	33	12%	20	7%
10500104	4	50%	1.00x	2	135	0.093	252	0.174	234	89	35%	88	35%	5	2%
10500105	5	50%	1.00x	2	181	0.130	256	0.184	212	32	13%	32	13%	12	5%
10750101	1	75%	1.00x	2	176	0.137	270	0.210	250	61	23%	56	21%	14	5%
10750102	2	75%	1.00x	2	135	0.106	177	0.140	169	24	14%	23	13%	8	5%
10750103	3	75%	1.00x	2	209	0.140	288	0.194	238	25	9%	25	9%	23	8%
10750104	4	75%	1.00x	2	153	0.106	255	0.176	230	73	29%	69	27%	12	5%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Maneuvers	Maneuvers per Aircraft	Conflicts	Conflicts per Aircraft	CD&R Invokes	Unresolved Conflicts	Unresolved Conflicts (%)	Unresolved Conflict Losses	Unresolved Conflict Losses (%)	Losses of Separation	Losses of Separation (%)
10750105	5	75%	1.00x	2	177	0.127	241	0.173	206	30	12%	30	12%	16	7%
11000101	1	100%	1.00x	2	192	0.150	271	0.211	246	45	17%	41	15%	17	6%
11000102	2	100%	1.00x	2	143	0.113	180	0.142	166	16	9%	15	8%	6	3%
11000103	3	100%	1.00x	2	222	0.149	293	0.197	243	20	7%	18	6%	24	8%
11000104	4	100%	1.00x	2	185	0.128	266	0.184	231	44	17%	42	16%	17	6%
11000105	5	100%	1.00x	2	201	0.144	254	0.182	214	14	6%	14	6%	20	8%
20000101	1	0%	1.00x	5	174	0.136	258	0.201	237	87	34%	81	31%	8	3%
20000102	2	0%	1.00x	5	160	0.126	186	0.146	177	38	20%	32	17%	8	4%
20000103	3	0%	1.00x	5	238	0.160	286	0.192	247	48	17%	47	16%	8	3%
20000104	4	0%	1.00x	5	192	0.133	268	0.185	267	85	32%	79	29%	7	3%
20000105	5	0%	1.00x	5	202	0.145	243	0.174	218	49	20%	46	19%	9	4%
20250101	1	25%	1.00x	5	159	0.124	267	0.208	247	90	34%	84	31%	6	2%
20250102	2	25%	1.00x	5	141	0.111	187	0.147	185	44	24%	43	23%	9	5%
20250103	3	25%	1.00x	5	219	0.147	294	0.197	265	61	21%	60	20%	8	3%
20250104	4	25%	1.00x	5	177	0.123	269	0.186	269	86	32%	79	29%	8	3%
20250105	5	25%	1.00x	5	192	0.138	260	0.187	233	47	18%	42	16%	11	4%
20500101	1	50%	1.00x	5	149	0.116	271	0.211	258	88	32%	84	31%	9	3%
20500102	2	50%	1.00x	5	130	0.102	190	0.149	182	43	23%	39	21%	7	4%
20500103	3	50%	1.00x	5	218	0.146	292	0.196	268	45	15%	43	15%	11	4%
20500104	4	50%	1.00x	5	157	0.109	263	0.182	267	89	34%	83	32%	8	3%
20500105	5	50%	1.00x	5	191	0.137	265	0.190	236	39	15%	37	14%	9	3%
20750101	1	75%	1.00x	5	167	0.130	275	0.214	263	66	24%	63	23%	8	3%
20750102	2	75%	1.00x	5	133	0.105	188	0.148	183	31	16%	30	16%	9	5%
20750103	3	75%	1.00x	5	216	0.145	293	0.197	259	32	11%	31	11%	13	4%
20750104	4	75%	1.00x	5	157	0.109	268	0.186	267	80	30%	74	28%	13	5%
20750105	5	75%	1.00x	5	188	0.135	263	0.189	240	35	13%	34	13%	13	5%
21000101	1	100%	1.00x	5	187	0.146	279	0.217	268	48	17%	46	16%	8	3%
21000102	2	100%	1.00x	5	148	0.116	187	0.147	191	14	7%	14	7%	13	7%
21000103	3	100%	1.00x	5	236	0.158	311	0.209	275	22	7%	22	7%	13	4%
21000104	4	100%	1.00x	5	190	0.132	266	0.184	273	41	15%	40	15%	17	6%
21000105	5	100%	1.00x	5	212	0.152	258	0.185	241	13	5%	13	5%	10	4%
30000101	1	0%	1.00x	10	201	0.157	266	0.207	256	101	38%	92	35%	5	2%
30000102	2	0%	1.00x	10	163	0.128	188	0.148	186	42	22%	40	21%	3	2%
30000103	3	0%	1.00x	10	278	0.187	292	0.196	258	55	19%	54	18%	4	1%
30000104	4	0%	1.00x	10	207	0.143	265	0.184	258	92	35%	79	30%	2	1%
30000105	5	0%	1.00x	10	191	0.137	238	0.171	213	52	22%	49	21%	5	2%
30250101	1	25%	1.00x	10	150	0.117	275	0.214	267	115	42%	108	39%	3	1%
30250102	2	25%	1.00x	10	145	0.114	189	0.149	182	51	27%	50	26%	4	2%
30250103	3	25%	1.00x	10	234	0.157	293	0.197	273	74	25%	69	24%	4	1%
30250104	4	25%	1.00x	10	174	0.120	264	0.183	261	102	39%	92	35%	2	1%
30250105	5	25%	1.00x	10	178	0.128	256	0.184	227	61	24%	55	21%	7	3%
30500101	1	50%	1.00x	10	147	0.114	285	0.222	285	110	39%	102	36%	3	1%
30500102	2	50%	1.00x	10	125	0.098	187	0.147	184	57	30%	52	28%	3	2%
30500103	3	50%	1.00x	10	201	0.135	283	0.190	267	68	24%	65	23%	2	1%
30500104	4	50%	1.00x	10	160	0.111	268	0.186	270	101	38%	93	35%	2	1%
30500105	5	50%	1.00x	10	178	0.128	260	0.187	236	59	23%	54	21%	10	4%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Maneuvers	Maneuvers per Aircraft	Conflicts	Conflicts per Aircraft	CD&R Invokes	Unresolved Conflicts	Unresolved Conflicts (%)	Unresolved Conflict Losses	Unresolved Conflict Losses (%)	Losses of Separation	Losses of Separation (%)
30750101	1	75%	1.00x	10	175	0.136	290	0.226	300	77	27%	72	25%	7	2%
30750102	2	75%	1.00x	10	125	0.098	183	0.144	184	44	24%	40	22%	4	2%
30750103	3	75%	1.00x	10	213	0.143	292	0.196	263	44	15%	43	15%	5	2%
30750104	4	75%	1.00x	10	158	0.109	268	0.186	272	87	32%	80	30%	5	2%
30750105	5	75%	1.00x	10	176	0.126	260	0.187	248	49	19%	47	18%	7	3%
31000101	1	100%	1.00x	10	222	0.173	305	0.238	315	43	14%	39	13%	9	3%
31000102	2	100%	1.00x	10	157	0.123	189	0.149	204	16	8%	15	8%	6	3%
31000103	3	100%	1.00x	10	248	0.166	307	0.206	282	16	5%	16	5%	6	2%
31000104	4	100%	1.00x	10	208	0.144	286	0.198	305	40	14%	40	14%	9	3%
31000105	5	100%	1.00x	10	220	0.158	266	0.191	262	13	5%	13	5%	9	3%
31000201	1	100%	2.00x	10	1118	0.401	1749	0.627	1116	63	4%	57	3%	39	2%
31000202	2	100%	2.00x	10	888	0.322	1235	0.447	857	26	2%	23	2%	37	3%
31000203	3	100%	2.00x	10	1427	0.440	2294	0.707	1284	31	1%	23	1%	65	3%
31000204	4	100%	2.00x	10	1166	0.370	1840	0.583	1177	63	3%	57	3%	53	3%
31000205	5	100%	2.00x	10	1135	0.371	1716	0.561	1050	30	2%	27	2%	46	3%
31000301	1	100%	3.00x	10	2659	0.619	4769	1.110	2130	85	2%	63	1%	128	3%
31000302	2	100%	3.00x	10	2174	0.508	3709	0.867	1769	51	1%	41	1%	109	3%
31000303	3	100%	3.00x	10	3367	0.674	6539	1.309	2405	68	1%	45	1%	192	3%
31000304	4	100%	3.00x	10	3014	0.618	5556	1.139	2328	108	2%	78	1%	154	3%
31000305	5	100%	3.00x	10	2720	0.581	4932	1.054	2066	57	1%	39	1%	153	3%
31000401	1	100%	4.00x	10	5006	0.861	10855	1.867	3263	187	2%	125	1%	311	3%
31000402	2	100%	4.00x	10	4081	0.707	8169	1.416	2730	104	1%	76	1%	265	3%
31000403	3	100%	4.00x	10	6087	0.904	14201	2.108	3612	220	2%	137	1%	434	3%
31000404	4	100%	4.00x	10	5501	0.836	12108	1.840	3416	228	2%	147	1%	363	3%
31000405	5	100%	4.00x	10	4875	0.773	10536	1.670	3131	168	2%	110	1%	302	3%
31000501	1	100%	5.00x	10	7700	1.055	19257	2.639	4187	359	2%	220	1%	605	3%
31000502	2	100%	5.00x	10	6388	0.877	15236	2.091	3618	220	1%	142	1%	425	3%
31000504	4	100%	5.00x	10	8377	1.015	21128	2.559	4297	449	2%	266	1%	617	3%
31000505	5	100%	5.00x	10	7571	0.955	19047	2.403	4028	348	2%	191	1%	577	3%
31001201	1	100%	1.25x	10	387	0.233	564	0.340	487	47	8%	41	7%	13	2%
31001202	2	100%	1.25x	10	261	0.159	331	0.201	317	16	5%	15	5%	11	3%
31001203	3	100%	1.25x	10	439	0.228	562	0.292	471	18	3%	17	3%	19	3%
31001204	4	100%	1.25x	10	372	0.199	500	0.268	469	45	9%	43	9%	13	3%
31001205	5	100%	1.25x	10	386	0.214	484	0.268	426	15	3%	15	3%	16	3%
31001501	1	100%	1.50x	10	594	0.291	858	0.420	690	50	6%	44	5%	23	3%
31001502	2	100%	1.50x	10	433	0.215	561	0.279	470	19	3%	18	3%	20	4%
31001503	3	100%	1.50x	10	684	0.289	969	0.409	697	22	2%	20	2%	27	3%
31001504	4	100%	1.50x	10	599	0.261	854	0.372	688	49	6%	48	6%	22	3%
31001505	5	100%	1.50x	10	588	0.264	811	0.365	612	20	2%	19	2%	22	3%
31001701	1	100%	1.75x	10	841	0.347	1267	0.523	888	53	4%	46	4%	31	2%
31001702	2	100%	1.75x	10	664	0.279	931	0.391	676	24	3%	23	2%	27	3%
31001703	3	100%	1.75x	10	990	0.353	1540	0.549	964	25	2%	21	1%	50	3%
31001704	4	100%	1.75x	10	904	0.332	1360	0.499	943	55	4%	53	4%	32	2%
31001705	5	100%	1.75x	10	836	0.318	1247	0.474	806	26	2%	23	2%	33	3%
31002501	1	100%	2.50x	10	1837	0.518	3101	0.875	1634	74	2%	59	2%	92	3%
31002502	2	100%	2.50x	10	1456	0.413	2272	0.645	1260	35	2%	28	1%	52	2%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Maneuvers	Maneuvers per Aircraft	Conflicts	Conflicts per Aircraft	CD&R Invokes	Unresolved Conflicts	Unresolved Conflicts (%)	Unresolved Conflict Losses	Unresolved Conflict Losses (%)	Losses of Separation	Losses of Separation (%)
31002503	3	100%	2.50x	10	2245	0.544	3989	0.967	1801	44	1%	31	1%	115	3%
31002504	4	100%	2.50x	10	2002	0.499	3408	0.849	1725	76	2%	62	2%	93	3%
31002505	5	100%	2.50x	10	1861	0.481	3084	0.796	1575	55	2%	40	1%	110	4%
40000101	1	0%	1.00x	30	203	0.158	258	0.201	239	101	39%	84	33%	4	2%
40000102	2	0%	1.00x	30	167	0.131	182	0.143	169	42	23%	32	18%	1	1%
40000103	3	0%	1.00x	30	325	0.218	287	0.192	255	53	18%	37	13%	5	2%
40000104	4	0%	1.00x	30	187	0.129	252	0.174	245	106	42%	80	32%	3	1%
40000105	5	0%	1.00x	30	253	0.182	245	0.176	215	53	22%	38	16%	7	3%
40250101	1	25%	1.00x	30	169	0.132	276	0.215	254	115	42%	91	33%	4	1%
40250102	2	25%	1.00x	30	145	0.114	182	0.143	169	59	32%	53	29%	1	1%
40250103	3	25%	1.00x	30	216	0.145	287	0.192	251	82	29%	65	23%	4	1%
40250104	4	25%	1.00x	30	174	0.120	259	0.179	252	121	47%	97	37%	2	1%
40250105	5	25%	1.00x	30	171	0.123	246	0.177	217	78	32%	63	26%	7	3%
40500101	1	50%	1.00x	30	149	0.116	281	0.219	256	112	40%	89	32%	3	1%
40500102	2	50%	1.00x	30	119	0.094	184	0.145	174	68	37%	54	29%	2	1%
40500103	3	50%	1.00x	30	186	0.125	285	0.191	262	90	32%	71	25%	4	1%
40500104	4	50%	1.00x	30	137	0.095	252	0.174	264	119	47%	98	39%	2	1%
40500105	5	50%	1.00x	30	163	0.117	245	0.176	218	75	31%	63	26%	7	3%
40750101	1	75%	1.00x	30	170	0.133	291	0.227	284	87	30%	71	24%	7	2%
40750102	2	75%	1.00x	30	120	0.094	180	0.142	174	51	28%	39	22%	2	1%
40750103	3	75%	1.00x	30	204	0.137	297	0.199	268	58	20%	44	15%	7	2%
40750104	4	75%	1.00x	30	154	0.107	268	0.186	283	95	35%	80	30%	4	1%
40750105	5	75%	1.00x	30	154	0.111	241	0.173	224	61	25%	53	22%	10	4%
41000101	1	100%	1.00x	30	214	0.167	306	0.239	302	43	14%	38	12%	10	3%
41000102	2	100%	1.00x	30	154	0.121	188	0.148	188	14	7%	14	7%	3	2%
41000103	3	100%	1.00x	30	246	0.165	310	0.208	279	18	6%	16	5%	10	3%
41000104	4	100%	1.00x	30	215	0.149	282	0.195	310	39	14%	38	13%	6	2%
41000105	5	100%	1.00x	30	211	0.151	263	0.189	243	13	5%	13	5%	10	4%
50000101	1	0%	1.00x	300	201	0.157	254	0.198	221	100	39%	76	30%	4	2%
50000102	2	0%	1.00x	300	165	0.130	178	0.140	161	42	24%	32	18%	2	1%
50000103	3	0%	1.00x	300	330	0.221	276	0.185	238	53	19%	35	13%	6	2%
50000104	4	0%	1.00x	300	216	0.149	256	0.177	237	106	41%	81	32%	1	0%
50000105	5	0%	1.00x	300	278	0.200	236	0.170	197	48	20%	34	14%	4	2%
50250101	1	25%	1.00x	300	163	0.127	272	0.212	234	116	43%	87	32%	4	1%
50250102	2	25%	1.00x	300	143	0.113	181	0.142	161	58	32%	52	29%	1	1%
50250103	3	25%	1.00x	300	220	0.148	277	0.186	232	86	31%	66	24%	3	1%
50250104	4	25%	1.00x	300	177	0.122	258	0.179	238	118	46%	96	37%	2	1%
50250105	5	25%	1.00x	300	169	0.121	239	0.172	193	73	31%	57	24%	6	3%
50500101	1	50%	1.00x	300	151	0.118	282	0.220	231	112	40%	89	32%	2	1%
50500102	2	50%	1.00x	300	117	0.092	182	0.143	164	64	35%	51	28%	2	1%
50500103	3	50%	1.00x	300	199	0.133	279	0.187	235	87	31%	69	25%	4	1%
50500104	4	50%	1.00x	300	137	0.095	250	0.173	241	120	48%	100	40%	3	1%
50500105	5	50%	1.00x	300	159	0.114	241	0.173	192	74	31%	60	25%	7	3%
50750101	1	75%	1.00x	300	171	0.133	293	0.228	249	88	30%	72	25%	5	2%
50750102	2	75%	1.00x	300	120	0.094	180	0.142	160	50	28%	38	21%	3	2%
50750103	3	75%	1.00x	300	197	0.132	291	0.195	237	56	19%	46	16%	3	1%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Maneuvers	Maneuvers per Aircraft	Conflicts	Conflicts per Aircraft	CD&R Invokes	Unresolved Conflicts	Unresolved Conflicts (%)	Unresolved Conflict Losses	Unresolved Conflict Losses (%)	Losses of Separation	Losses of Separation (%)
50750104	4	75%	1.00x	300	149	0.103	261	0.181	249	95	36%	80	31%	4	2%
50750105	5	75%	1.00x	300	158	0.114	247	0.177	198	60	24%	51	21%	10	4%
51000101	1	100%	1.00x	300	214	0.167	307	0.239	261	43	14%	38	12%	8	3%
51000102	2	100%	1.00x	300	150	0.118	185	0.145	170	14	8%	14	8%	4	2%
51000103	3	100%	1.00x	300	239	0.160	303	0.203	243	18	6%	16	5%	6	2%
51000104	4	100%	1.00x	300	214	0.148	277	0.192	264	40	14%	39	14%	5	2%
51000105	5	100%	1.00x	300	208	0.149	265	0.190	205	13	5%	13	5%	11	4%

Table 6 Active aircraft, actual cost index, and timing data

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Average Active Aircraft	Average Centralized Active Aircraft	Average Decentralized Active Aircraft	Actual Centralized Cost Index	Total Wall Clock Time (min)	Simulation Time (min)	Speedup	CD&R Time (min)	CD&R Time (%)
10000101	1	0%	1.00x	2	112.9	112.9	0.0	48.80	33.80	33.52	8.951	12.13	36%
10000102	2	0%	1.00x	2	109.0	109.0	0.0	49.71	27.12	26.60	11.278	7.13	27%
10000103	3	0%	1.00x	2	129.9	129.9	0.0	48.99	45.28	44.48	6.744	14.93	34%
10000104	4	0%	1.00x	2	126.1	126.1	0.0	49.90	42.48	40.95	7.326	14.32	35%
10000105	5	0%	1.00x	2	121.8	121.8	0.0	49.94	35.47	34.33	8.738	10.43	30%
10250101	1	25%	1.00x	2	113.0	85.2	27.8	48.51	30.10	28.77	10.429	6.82	24%
10250102	2	25%	1.00x	2	109.0	80.0	29.1	49.33	25.15	23.67	12.676	3.95	17%
10250103	3	25%	1.00x	2	130.0	97.6	32.4	49.16	51.63	49.85	6.018	8.55	17%
10250104	4	25%	1.00x	2	126.2	95.2	30.9	49.57	41.77	39.13	7.666	8.05	21%
10250105	5	25%	1.00x	2	121.9	88.4	33.4	50.01	33.05	29.88	10.039	5.57	19%
10500101	1	50%	1.00x	2	113.1	57.1	56.0	49.43	77.78	75.47	3.975	9.98	13%
10500102	2	50%	1.00x	2	109.1	54.0	55.1	49.99	36.72	33.78	8.880	4.45	13%
10500103	3	50%	1.00x	2	130.0	64.9	65.1	48.68	80.35	77.18	3.887	8.08	10%
10500104	4	50%	1.00x	2	126.1	63.9	62.2	50.01	123.22	119.73	2.506	13.30	11%
10500105	5	50%	1.00x	2	122.0	58.4	63.6	49.74	47.25	44.32	6.769	6.75	15%
10750101	1	75%	1.00x	2	113.2	29.3	83.8	47.74	203.58	200.77	1.494	20.63	10%
10750102	2	75%	1.00x	2	109.1	27.0	82.1	50.31	67.97	65.08	4.609	7.32	11%
10750103	3	75%	1.00x	2	129.9	30.9	99.0	47.63	141.20	137.87	2.176	11.90	9%
10750104	4	75%	1.00x	2	126.2	32.2	94.0	48.87	333.72	330.28	0.908	23.50	7%
10750105	5	75%	1.00x	2	122.0	29.0	93.0	49.81	90.70	87.17	3.442	11.33	13%
11000101	1	100%	1.00x	2	113.2	0.0	113.2		730.63	726.93	0.413	37.90	5%
11000102	2	100%	1.00x	2	109.1	0.0	109.1		141.65	138.12	2.172	10.47	8%
11000103	3	100%	1.00x	2	130.0	0.0	130.0		229.65	226.40	1.325	18.15	8%
11000104	4	100%	1.00x	2	126.2	0.0	126.2		749.27	745.67	0.402	39.10	5%
11000105	5	100%	1.00x	2	122.0	0.0	122.0		135.68	135.25	2.218	14.20	10%
20000101	1	0%	1.00x	5	113.1	113.1	0.0	48.80	37.90	37.52	7.996	15.03	40%
20000102	2	0%	1.00x	5	109.1	109.1	0.0	49.71	28.57	28.03	10.702	7.87	28%
20000103	3	0%	1.00x	5	130.0	130.0	0.0	48.99	44.35	43.75	6.857	13.98	32%
20000104	4	0%	1.00x	5	126.2	126.2	0.0	49.90	45.03	44.53	6.737	16.80	38%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Average Active Aircraft	Average Centralized Active Aircraft	Average Decentralized Active Aircraft	Actual Centralized Cost Index	Total Wall Clock Time (min)	Simulation Time (min)	Speedup	CD&R Time (min)	CD&R Time (%)
20000105	5	0%	1.00x	5	122.1	122.1	0.0	49.94	34.65	34.10	8.798	10.02	29%
20250101	1	25%	1.00x	5	113.2	85.3	27.9	48.51	31.10	30.73	9.761	7.87	26%
20250102	2	25%	1.00x	5	109.4	80.1	29.2	49.33	25.07	24.65	12.170	4.68	19%
20250103	3	25%	1.00x	5	130.0	97.6	32.4	49.16	38.87	38.23	7.847	8.42	22%
20250104	4	25%	1.00x	5	126.2	95.2	30.9	49.57	38.53	37.90	7.916	9.23	24%
20250105	5	25%	1.00x	5	122.1	88.5	33.5	50.01	32.05	30.53	9.825	5.95	19%
20500101	1	50%	1.00x	5	113.2	57.1	56.1	49.43	30.73	30.28	9.906	7.32	24%
20500102	2	50%	1.00x	5	109.4	54.1	55.2	49.99	24.68	23.97	12.517	3.92	16%
20500103	3	50%	1.00x	5	130.2	64.9	65.4	48.68	40.07	39.65	7.566	7.83	20%
20500104	4	50%	1.00x	5	126.3	63.9	62.4	50.01	35.32	34.72	8.641	7.42	21%
20500105	5	50%	1.00x	5	122.2	58.5	63.7	49.74	32.00	31.30	9.585	6.18	20%
20750101	1	75%	1.00x	5	113.2	29.3	83.9	47.74	32.68	31.93	9.395	8.52	27%
20750102	2	75%	1.00x	5	109.3	27.0	82.3	50.31	24.07	23.77	12.623	4.22	18%
20750103	3	75%	1.00x	5	130.1	30.9	99.2	47.63	38.53	38.13	7.867	7.68	20%
20750104	4	75%	1.00x	5	126.4	32.2	94.2	48.87	38.80	38.37	7.819	8.63	23%
20750105	5	75%	1.00x	5	122.2	29.0	93.2	49.81	31.55	31.05	9.662	6.40	21%
21000101	1	100%	1.00x	5	113.3	0.0	113.3		35.40	35.05	8.559	10.25	29%
21000102	2	100%	1.00x	5	109.3	0.0	109.3		26.02	25.72	11.666	4.87	19%
21000103	3	100%	1.00x	5	130.2	0.0	130.2		42.07	41.60	7.212	9.53	23%
21000104	4	100%	1.00x	5	126.5	0.0	126.5		39.35	38.78	7.735	8.85	23%
21000105	5	100%	1.00x	5	122.2	0.0	122.2		35.27	34.00	8.824	7.68	23%
30000101	1	0%	1.00x	10	113.2	113.2	0.0	48.80	49.75	49.42	6.071	27.13	55%
30000102	2	0%	1.00x	10	109.2	109.2	0.0	49.71	31.23	30.70	9.772	10.47	34%
30000103	3	0%	1.00x	10	130.0	130.0	0.0	48.99	49.20	48.20	6.224	19.23	40%
30000104	4	0%	1.00x	10	126.3	126.3	0.0	49.90	44.68	44.23	6.782	16.68	38%
30000105	5	0%	1.00x	10	122.0	122.0	0.0	49.94	35.80	35.43	8.467	10.97	31%
30250101	1	25%	1.00x	10	113.2	85.4	27.9	48.51	33.03	32.65	9.188	10.78	33%
30250102	2	25%	1.00x	10	109.3	80.2	29.2	49.33	26.17	25.83	11.613	5.47	21%
30250103	3	25%	1.00x	10	130.2	97.7	32.4	49.16	38.98	38.43	7.806	8.80	23%
30250104	4	25%	1.00x	10	126.2	95.3	31.0	49.57	37.60	37.12	8.083	9.72	26%
30250105	5	25%	1.00x	10	122.0	88.5	33.5	50.01	33.33	31.83	9.424	7.10	22%
30500101	1	50%	1.00x	10	113.3	57.2	56.1	49.43	33.17	32.88	9.123	9.12	28%
30500102	2	50%	1.00x	10	109.4	54.1	55.3	49.99	25.72	25.30	11.858	4.65	18%
30500103	3	50%	1.00x	10	130.2	64.9	65.3	48.68	39.78	39.37	7.621	8.10	21%
30500104	4	50%	1.00x	10	126.2	63.9	62.3	50.01	40.55	40.03	7.494	10.15	25%
30500105	5	50%	1.00x	10	121.9	58.4	63.5	49.74	33.13	32.30	9.288	7.05	22%
30750101	1	75%	1.00x	10	113.4	29.3	84.1	47.74	38.08	37.78	7.940	11.95	32%
30750102	2	75%	1.00x	10	109.4	27.0	82.3	50.31	26.58	26.05	11.516	5.12	20%
30750103	3	75%	1.00x	10	130.2	30.9	99.3	47.63	40.87	40.48	7.410	9.38	23%
30750104	4	75%	1.00x	10	126.3	32.2	94.1	48.87	42.80	42.15	7.117	11.10	26%
30750105	5	75%	1.00x	10	122.1	29.0	93.1	49.81	32.92	32.12	9.341	7.25	23%
31000101	1	100%	1.00x	10	113.5	0.0	113.5		43.65	43.27	6.934	14.35	33%
31000102	2	100%	1.00x	10	109.5	0.0	109.5		29.30	29.03	10.333	7.23	25%
31000103	3	100%	1.00x	10	130.4	0.0	130.4		45.20	44.68	6.714	12.77	29%
31000104	4	100%	1.00x	10	126.5	0.0	126.5		49.52	49.07	6.114	14.47	29%
31000105	5	100%	1.00x	10	122.2	0.0	122.2		36.75	35.75	8.392	9.88	28%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Average Active Aircraft	Average Centralized Active Aircraft	Average Decentralized Active Aircraft	Actual Centralized Cost Index	Total Wall Clock Time (min)	Simulation Time (min)	Speedup	CD&R Time (min)	CD&R Time (%)
31000201	1	100%	2.00x	10	251.4	0.0	251.4		337.05	336.27	0.892	173.48	52%
31000202	2	100%	2.00x	10	243.6	0.0	243.6		250.17	247.78	1.211	111.40	45%
31000203	3	100%	2.00x	10	292.0	0.0	292.0		445.32	442.77	0.678	244.80	55%
31000204	4	100%	2.00x	10	281.8	0.0	281.8		399.88	398.48	0.753	201.33	51%
31000205	5	100%	2.00x	10	272.0	0.0	272.0		317.63	316.62	0.948	155.73	49%
31000301	1	100%	3.00x	10	390.2	0.0	390.2		1277.08	1275.42	0.235	834.92	65%
31000302	2	100%	3.00x	10	379.6	0.0	379.6		930.93	927.22	0.324	559.78	60%
31000303	3	100%	3.00x	10	453.3	0.0	453.3		2087.97	2080.53	0.144	1480.08	71%
31000304	4	100%	3.00x	10	441.0	0.0	441.0		1794.70	1792.02	0.167	1218.15	68%
31000305	5	100%	3.00x	10	420.8	0.0	420.8		1326.43	1324.42	0.227	880.57	66%
31000401	1	100%	4.00x	10	533.5	0.0	533.5		4945.00	4939.35	0.061	3763.43	76%
31000402	2	100%	4.00x	10	518.0	0.0	518.0		2922.03	2908.95	0.103	2096.85	72%
31000403	3	100%	4.00x	10	619.2	0.0	619.2		8098.40	8084.45	0.037	6388.08	79%
31000404	4	100%	4.00x	10	599.6	0.0	599.6		6239.35	6235.37	0.048	4834.37	78%
31000405	5	100%	4.00x	10	570.2	0.0	570.2		4596.92	4578.03	0.066	3457.20	76%
31000501	1	100%	5.00x	10	678.3	0.0	678.3		14408.67	14403.68	0.021	11614.70	81%
31000502	2	100%	5.00x	10	657.8	0.0	657.8		9317.33	9300.77	0.032	7368.80	79%
31000504	4	100%	5.00x	10	755.2	0.0	755.2		17184.75	17176.32	0.017	13757.10	80%
31000505	5	100%	5.00x	10	719.8	0.0	719.8		13262.77	13242.87	0.023	10611.48	80%
31001201	1	100%	1.25x	10	149.1	0.0	149.1		88.60	88.08	3.406	34.93	40%
31001202	2	100%	1.25x	10	141.7	0.0	141.7		56.72	55.12	5.443	15.52	28%
31001203	3	100%	1.25x	10	170.1	0.0	170.1		86.02	85.48	3.509	27.43	32%
31001204	4	100%	1.25x	10	163.5	0.0	163.5		89.08	88.30	3.398	29.50	33%
31001205	5	100%	1.25x	10	159.0	0.0	159.0		70.35	69.80	4.298	21.90	31%
31001501	1	100%	1.50x	10	182.1	0.0	182.1		139.85	139.20	2.155	58.67	42%
31001502	2	100%	1.50x	10	175.0	0.0	175.0		97.48	95.82	3.131	31.57	33%
31001503	3	100%	1.50x	10	210.3	0.0	210.3		156.68	155.95	1.924	64.05	41%
31001504	4	100%	1.50x	10	202.2	0.0	202.2		147.62	146.77	2.044	57.93	39%
31001505	5	100%	1.50x	10	196.4	0.0	196.4		128.27	127.68	2.350	49.15	38%
31001701	1	100%	1.75x	10	215.9	0.0	215.9		221.77	221.28	1.356	105.07	47%
31001702	2	100%	1.75x	10	207.7	0.0	207.7		158.92	156.25	1.920	61.15	39%
31001703	3	100%	1.75x	10	250.1	0.0	250.1		243.35	242.48	1.237	113.05	47%
31001704	4	100%	1.75x	10	240.9	0.0	240.9		247.52	246.73	1.216	112.85	46%
31001705	5	100%	1.75x	10	232.9	0.0	232.9		198.98	198.47	1.512	83.47	42%
31002501	1	100%	2.50x	10	321.0	0.0	321.0		663.12	661.93	0.453	390.15	59%
31002502	2	100%	2.50x	10	310.5	0.0	310.5		481.43	477.88	0.628	254.32	53%
31002503	3	100%	2.50x	10	373.0	0.0	373.0		1020.33	1016.55	0.295	670.58	66%
31002504	4	100%	2.50x	10	359.3	0.0	359.3		837.20	835.45	0.359	490.38	59%
31002505	5	100%	2.50x	10	346.4	0.0	346.4		650.27	648.83	0.462	375.50	58%
40000101	1	0%	1.00x	30	113.1	113.1	0.0	48.80	306.22	305.95	0.981	283.90	93%
40000102	2	0%	1.00x	30	109.3	109.3	0.0	49.71	36.43	36.05	8.322	15.52	43%
40000103	3	0%	1.00x	30	130.1	130.1	0.0	48.99	63.00	62.60	4.792	32.35	52%
40000104	4	0%	1.00x	30	126.3	126.3	0.0	49.90	85.12	84.50	3.550	56.25	67%
40000105	5	0%	1.00x	30	122.0	122.0	0.0	49.94	53.32	51.93	5.777	26.57	51%
40250101	1	25%	1.00x	30	113.2	85.4	27.9	48.51	171.88	171.52	1.749	148.35	86%
40250102	2	25%	1.00x	30	109.3	80.1	29.1	49.33	29.13	28.83	10.405	8.32	29%

Run ID	Scenario	Locus of Control (% Decentralized)	Traffic Density	Look-ahead Time (min)	Average Active Aircraft	Average Centralized Active Aircraft	Average Decentralized Active Aircraft	Actual Centralized Cost Index	Total Wall Clock Time (min)	Simulation Time (min)	Speedup	CD&R Time (min)	CD&R Time (%)
40250103	3	25%	1.00x	30	130.1	97.7	32.4	49.16	46.23	45.83	6.545	14.92	33%
40250104	4	25%	1.00x	30	126.3	95.3	30.9	49.57	48.23	47.87	6.267	18.80	39%
40250105	5	25%	1.00x	30	121.9	88.6	33.4	50.01	39.08	38.73	7.745	13.43	35%
40500101	1	50%	1.00x	30	113.3	57.2	56.1	49.43	42.15	41.75	7.186	15.88	38%
40500102	2	50%	1.00x	30	109.2	54.1	55.2	49.99	31.23	30.87	9.719	9.03	29%
40500103	3	50%	1.00x	30	130.1	64.9	65.2	48.68	47.53	47.17	6.360	14.37	30%
40500104	4	50%	1.00x	30	126.2	63.9	62.3	50.01	52.53	52.20	5.747	18.70	36%
40500105	5	50%	1.00x	30	122.1	58.5	63.7	49.74	38.68	37.35	8.032	11.15	30%
40750101	1	75%	1.00x	30	113.4	29.3	84.1	47.74	49.15	48.92	6.133	18.92	39%
40750102	2	75%	1.00x	30	109.4	27.0	82.3	50.31	34.02	33.70	8.902	10.02	30%
40750103	3	75%	1.00x	30	130.1	30.9	99.2	47.63	54.33	54.07	5.549	19.33	36%
40750104	4	75%	1.00x	30	126.4	32.2	94.2	48.87	60.30	60.07	4.994	22.62	38%
40750105	5	75%	1.00x	30	122.2	29.0	93.2	49.81	40.48	39.32	7.630	11.93	30%
41000101	1	100%	1.00x	30	113.4	0.0	113.4		72.43	72.17	4.157	30.08	42%
41000102	2	100%	1.00x	30	109.4	0.0	109.4		37.78	37.60	7.979	11.42	30%
41000103	3	100%	1.00x	30	130.3	0.0	130.3		59.10	58.87	5.096	22.87	39%
41000104	4	100%	1.00x	30	126.5	0.0	126.5		76.77	76.30	3.932	31.80	42%
41000105	5	100%	1.00x	30	122.3	0.0	122.3		50.67	50.27	5.968	20.83	41%
50000101	1	0%	1.00x	300	113.1	113.1	0.0	48.80	339.33	339.02	0.885	316.77	93%
50000102	2	0%	1.00x	300	109.2	109.2	0.0	49.71	44.77	44.50	6.742	23.92	54%
50000103	3	0%	1.00x	300	130.1	130.1	0.0	48.99	84.97	84.43	3.553	53.67	64%
50000104	4	0%	1.00x	300	126.3	126.3	0.0	49.90	121.60	121.03	2.479	91.95	76%
50000105	5	0%	1.00x	300	122.0	122.0	0.0	49.94	76.00	75.58	3.969	50.05	66%
50250101	1	25%	1.00x	300	113.2	85.4	27.9	48.51	189.57	189.28	1.585	165.92	88%
50250102	2	25%	1.00x	300	109.2	80.1	29.1	49.33	33.12	32.78	9.151	12.28	37%
50250103	3	25%	1.00x	300	130.1	97.7	32.4	49.16	54.70	54.20	5.535	23.00	42%
50250104	4	25%	1.00x	300	126.2	95.3	30.9	49.57	60.95	60.52	4.957	31.53	52%
50250105	5	25%	1.00x	300	122.1	88.6	33.5	50.01	47.50	46.88	6.399	20.98	45%
50500101	1	50%	1.00x	300	113.3	57.2	56.1	49.43	47.87	47.50	6.316	20.87	44%
50500102	2	50%	1.00x	300	109.2	54.1	55.1	49.99	32.52	32.17	9.326	10.30	32%
50500103	3	50%	1.00x	300	130.1	64.9	65.2	48.68	53.47	52.80	5.682	19.45	37%
50500104	4	50%	1.00x	300	126.2	63.9	62.3	50.01	56.85	56.30	5.329	22.90	41%
50500105	5	50%	1.00x	300	122.0	58.5	63.5	49.74	42.77	41.70	7.194	15.28	37%
50750101	1	75%	1.00x	300	113.4	29.3	84.0	47.74	56.22	55.87	5.370	24.20	43%
50750102	2	75%	1.00x	300	109.2	27.0	82.2	50.31	36.67	35.95	8.345	11.97	33%
50750103	3	75%	1.00x	300	130.1	30.9	99.2	47.63	62.52	62.18	4.824	25.28	41%
50750104	4	75%	1.00x	300	126.3	32.2	94.1	48.87	65.92	65.50	4.580	26.95	41%
50750105	5	75%	1.00x	300	122.2	29.0	93.2	49.81	44.13	43.08	6.963	15.62	36%
51000101	1	100%	1.00x	300	113.4	0.0	113.4		78.40	78.12	3.840	35.75	46%
51000102	2	100%	1.00x	300	109.4	0.0	109.4		40.00	39.72	7.554	13.22	33%
51000103	3	100%	1.00x	300	130.3	0.0	130.3		65.10	64.77	4.632	27.50	42%
51000104	4	100%	1.00x	300	126.5	0.0	126.5		88.48	88.03	3.408	41.10	47%
51000105	5	100%	1.00x	300	122.2	0.0	122.2		55.50	54.95	5.460	24.63	45%

A.2 Centralized CD&R Pruning Data

The data used to calculate the centralized CD&R implementation pruning statistics can be found in Table 7 with a summary in Table 8.

Table 7 Centralized CD&R implementation pruning data

Run ID	Sim Time	Max Tree Depth	End Branches (w/)	End Branches (w/o)	Forks (w/)	Forks (w/o)	Cost (w/) (lbm)	Cost (w/o) (lbm)	Time (w/) (s)	Time (w/o) (s)	Cost Difference (lbm)	Time Difference (s)	Time Difference (>0) (s)
10000102	495.0	2	0	0	4	4	0.000	0.000	0	0	0.000	0	
10000102	727.0	1	4	7	2	2	4.439	4.439	0	1	0.000	1	1
10000102	959.3	3	4	24	17	313	5.548	5.548	7	136	0.000	129	129
20000101	89.0	1	2	3	1	1	-1.597	-1.597	1	1	0.000	0	
20000102	495.0	2	0	0	4	4	0.000	0.000	1	0	0.000	-1	
20000102	727.0	3	13	4095	24	990	5.548	5.548	10	354	0.000	344	344
20000103	455.0	1	3	4	1	1	-10.688	-10.688	1	0	0.000	-1	
20000103	897.0	1	1	10	1	1	-10.293	-10.293	1	0	0.000	-1	
20000103	910.0	2	6	114	6	32	-27.456	-27.456	4	21	0.000	17	17
20000104	291.0	2	0	0	4	4	0.000	0.000	3	2	0.000	-1	
30000102	495.0	3	0	0	29	29	0.000	0.000	2	1	0.000	-1	
30000102	529.0	2	4	222	6	44	1.109	1.109	3	20	0.000	17	17
30000103	455.0	1	3	4	1	1	-10.688	-10.688	1	0	0.000	-1	
30000103	754.0	1	2	3	1	1	-0.952	-0.952	2	1	0.000	-1	
30000103	988.0	3	3	6	8	25	25.264	25.264	4	16	0.000	12	12
30000103	1123.5	3	6	740	11	269	30.388	30.388	7	215	0.000	208	208
30000103	1185.0	1	0	0	1	1	0.000	0.000	0	0	0.000	0	
30000104	291.0	3	0	0	5	5	0.000	0.000	8	9	0.000	1	1
30000105	324.0	2	12	126	5	18	-238.637	-241.930	4	14	3.293	10	10
40000105	324.0	3	12	1944	13	333	-237.114	-240.407	18	479	3.293	461	461
40000105	440.0	2	2	70	7	14	-185.557	-245.949	80	119	60.393	39	39
50000102	111.0	1	2	4	1	1	3.370	3.370	1	1	0.000	0	
50000102	116.0	1	2	6	1	1	7.657	7.657	3	2	0.000	-1	
50000102	495.0	4	0	0	31	31	0.000	0.000	11	10	0.000	-1	
50000102	727.0	3	6	908	8	269	22.388	15.543	19	481	6.845	462	462
50000102	959.3	2	0	0	7	7	0.000	0.000	21	21	0.000	0	
50000102	1274.0	3	0	0	134	134	0.000	0.000	265	268	0.000	3	3
50000102	2132.0	6	3	23	262	656	26.401	26.401	259	615	0.000	356	356
50000102	2162.0	3	0	0	92	92	0.000	0.000	206	207	0.000	1	1
50000102	2227.0	2	3	162	3	20	14.884	14.884	201	1346	0.000	1145	1145
50000102	2508.0	2	4	18	6	16	4.065	407.755	12	29	403.690	17	17
50000102	2739.0	1	2	6	1	1	401.601	401.601	2	2	0.000	0	

Table 8 Centralized CD&R implementation pruning data summary

Value	Cost Difference (lbm)	Time Difference (s)	Time Difference (>0) (s)
Average	14.922	100.438	189.588
Standard Deviation	71.742	235.674	299.329
Difference Percentage	15.63%	53.13%	
Significant Difference (≥10)	6.25%	40.63%	

APPENDIX B

SIMULATION DETAILS

B.1 Simulation Hardware Specifications

Two identical compute nodes were used for all of the simulation runs. Each node had dual Intel Xeon X5660 processors running at 2.8GHz with 12MB of cache and 24GB of memory.

B.2 Simulation Software Specifications

The operating system on the compute nodes was Red Hat Enterprise Linux version 5 with kernel version 2.6.18-238.1.1.el5 compiled for symmetric multiprocessing (SMP) and the x86_64 architecture. The vanilla universe of Condor version 7.4.1 was used for job submission and execution. A number of additional software packages were compiled and run in user space in order to generate the simulation binaries. They are listed in the order of installation along with their configuration command:

1) gmp-5.0.1:

```
./configure --prefix=$HOME/local --enable-cxx --enable-mpbsd
```

2) mpfr-3.0.0:

```
./configure --prefix=$HOME/local --enable-thread-safe
```

3) mpc-0.9:

```
./configure --prefix=$HOME/local
```

4) gcc-4.6.0-RC-20110314:

```
./configure --prefix=$HOME/local --libexecdir=$HOME/local/lib
--enable-shared --enable-threads=posix --enable-__cxa_atexit
--enable-clocale=gnu --enable-languages=c,c++ --disable-multilib
--disable-bootstrap --with-system-zlib
```

5) cmake-2.8.4 (bootstrapped with the same prefix parameter as above)

6) mysql-connector-c-6.0.2-linux-rhel5-x86-64bit (binaries)

The purpose of installing the first four of these packages was to have a compiler (GCC) that supported C++0x, which is the version of C++ that WMC is primarily written in. GCC version 4.5 or greater as well as CMake version 2.6 or greater is necessary to be able to compile WMC on a Linux platform. The MySQL connector libraries were necessary to interface with the MySQL database where all the run data was stored. Several path variables (CPATH, LIBRARY_PATH, LD_LIBRARY_PATH, MYSQL_DIR, and MYSQL_LIB) were then set to point to the local library and include folders so compilation and execution would use the local paths instead of the system paths.

B.3 Additional Software Tools

B.3.1 ETMS and Run Configuration Data Manipulation and Insertion

Microsoft Excel 2010 was used for manipulation of the ETMS data into the proper format for the simulation database. First, the ETMS data was imported into Excel, filtered by the Indianapolis Center, and the time the aircraft entered the center (from 1pm to 6pm, local time). The remaining data (for each of 5 days) was copied into another worksheet and a column was added that determined if the aircraft started and/or ended at or above FL180. The data was then filtered by this column, and the aircraft starting and ending below FL180 were deleted. The data was then sorted by entrance time and each aircraft was assigned a name beginning with AC and ending with a 0-padded 4 digit number in ascending order starting from 1. The two random numbers were generated using Excel's RAND function. For each scenario, the locus of control assignment number started as a list from 1 to the number of aircraft in the scenario. The whole scenario dataset was then sorted by a column consisting of random values, the locus of control column was then cut, the dataset resorted by aircraft name, then pasted back in so that the locus of control number column was now in random order. The cost index column was simply the RAND function scaled appropriately to generate a range from 0 to 100. Finally, the flight levels were converted to altitudes and the time stamps were converted to seconds with 0 seconds equaling 1pm local time.

After each scenario aircraft and waypoint dataset was ready, each scenario aircraft dataset was copied into one large aircraft dataset and likewise with each scenario waypoint dataset. Microsoft Access 2010 was then used with a MySQL ODBC (Open DataBase Connectivity) connection to accept a large paste request from Excel for the aircraft and waypoint datasets. Excel was also used to generate the many run configuration settings that were also pasted into Access and thus the MySQL database.

B.3.2 Data Output and Visualization

Microsoft Excel with a MySQL ODBC connection was used to retrieve the run summary data found in tables 2-6. The pivot table and chart tools were used extensively to process and display the results. A PHP script was written to directly access the MySQL database and produce KML (Keyhole Markup Language) files that Google Earth can use to display all the aircraft data from entire runs. The Google Earth visualization was used to not only debug larger-scale simulation issues, but also as a visualization tool for examining specific portions of the simulation runs, as in section 4.1.5.

B.4 Database Design

An SQL (Structured Query Language) database was needed to provide an organized, high-performance, accessible storage space for input and output to and from the simulator. MySQL with the MyISAM storage engine was used along with the table design shown in Figure 32. Several additional views are not shown that are used by the run_summary view to produce the data seen in tables 2-6. The contents of the aircraft_input, waypoint_input and (part of the) runs tables are described in section B.3.1, the simulation outputs aircraft state data to raw_output, aircraft summary data to summarized_output, airspace state data to airspace_output, (unresolved) conflicts, losses of separation, etc. to events, and CD&R and other failures to issues. The view_criteria table enables the limiting of returned data through several views not shown in Figure 32.

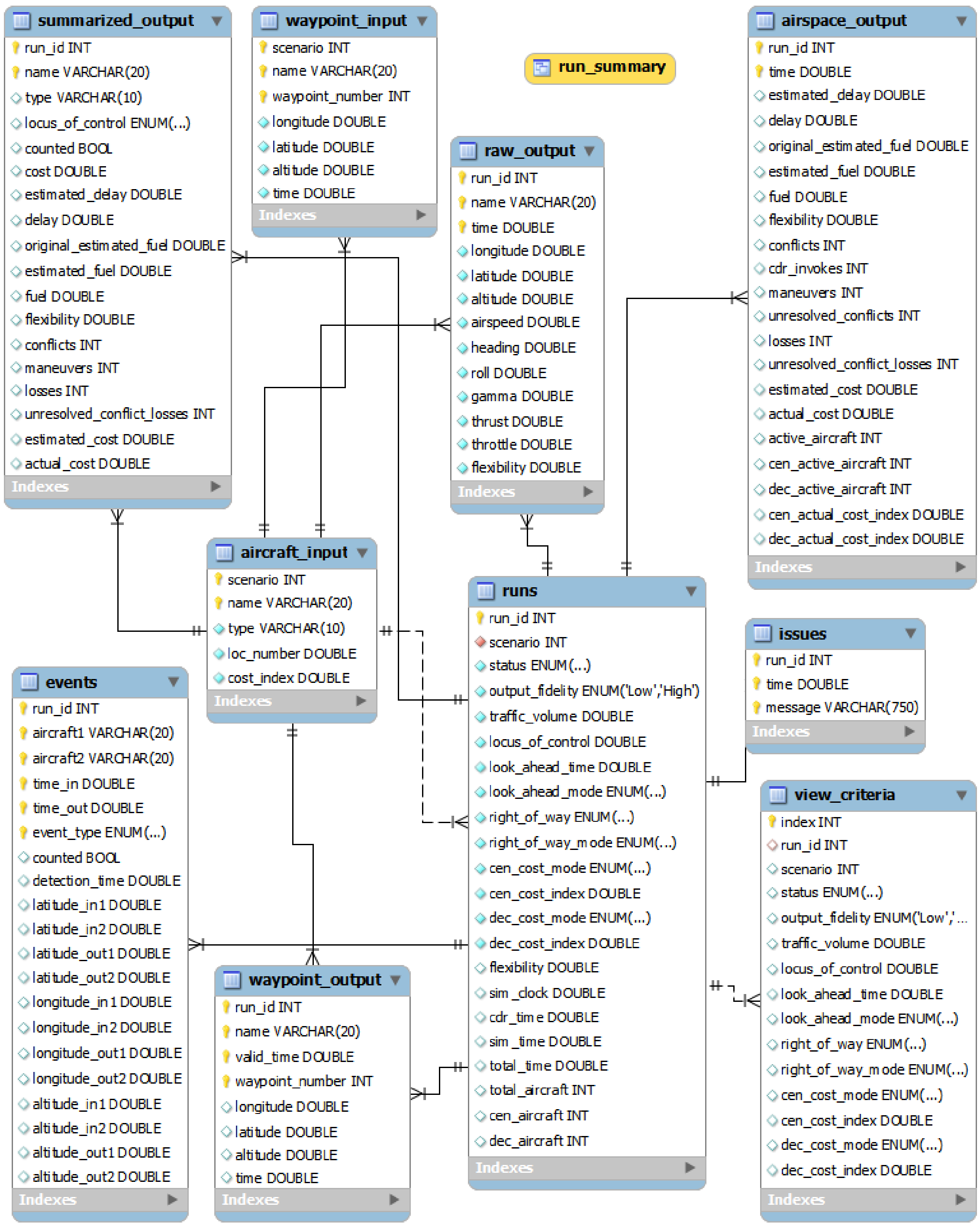

Figure 32 Database table layout diagram

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